Lab Report
EE2E11

Power transfer with an air core transformer

Group 33

TU Delft

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Power transfer

with an air core transformer

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Contents

1 Introduction

During the lectures of *EE2E11: Electrical Energy Conversion* we have learned about electrical conversion topologies and related efficiency and power calculations. At *EE2C11: Integrated Circuits* we learned about semiconductor devices, including MOSFETS. In the EE2E11 Course Labs we used the acquired knowledge to build an air core transformer system: wireless power transfer.

This both had us get acquainted with the physical devices and elements involved with the learned theory, and gave us the chance to gain some experience with engineering a power system, especially regarding compensation for nonideal components, measurements and circumstances.

We especially learned that sometimes manual optimization is a better solution than trying to get perfect measurements and calculated values.

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Design Requirements and Choices

The system to be designed is a wireless power transfer DC-DC converter which is able to charge a 20 V battery from a 20 V power supply. This system can be subdivided into multiple smaller subsystems, namely an inverter, an air coupled transformer and a rectifier. The inverter converts the DC voltage from the power supply to high frequency AC. The air coupled transformer then transfers this power wirelessly to the rectifier. And the rectifier then converts it back to DC.

2.1. Inverter

The task of the inverter is to convert the 20 V input to an AC output and to protect the load from too high currents.

2.1.1. H-bridge

The conversion from DC to AC is achieved with an H-bridge. The H-bridge is a circuit consisting of four switches, in this case MOSFETs, with a load connected in the middle, see Figure 2.1. By alternating the path from the supply voltage to ground through the load, the DC supply is converted to AC. Two MOSFET types

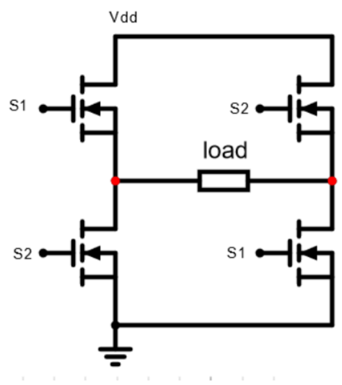

Figure 2.1: H-bridge circuit diagram

were made available, the PSMN017-80PS and the IPP530N15N3 G, both N-channel MOSFETs but with different electrical characteristics. The most relevant differences are that the PSMN017-80PS has a lower on-state drain-source resistance (R_{DS}), 13.7 mΩ[6] against 44 mΩ for the IPP530N15N3 G[4] but longer switch times. However, the relatively long switch times of the PSMN017-80PS are still well within the range allowed by the rest of the circuit, especially since the gate driver has an output delay matching tolerance of 50 ns. For this reason and because the lower on-state R_{DS} is beneficial to the theoretical efficiency potential of the circuit, we chose the PSMN017-80PS, to use in the circuit. The transistors are driven by the IRS2001 gate driver IC and is connected like its typical connection diagram found in the datasheet[3]. This IC can generate high voltages to control the gates of high-side FETs. These voltages can rise high enough to deliver a shock to nearby limbs or metal objects, therefore the inverter is placed inside a protective casing.

2.1.2. PWM generator

The control signal for the transistors is generated by a PWM generator IC, the UC3525A. This device generates a square wave with variable duty cycle and frequency proportional to the resistance, in this case variable resistors, connected to two of its pins. The generated signal is sent to one half of the bridge and an inverse of the signal is sent to the other half. To ensure the two halves of the bridge are never on at the same time, a dead time resistor is added to one of the pins of the IC. The IC is connected like its typical connection diagram found in the datasheet[7].

2.1.3. Overcurrent protection

To ensure the current levels that would break the circuit are blocked, a overcurrent protection is added to the inverter. This protection measures the voltage of a shunt resistor and compares it to a maximum voltage value via a comparator. This output is then inverted and used as the clock input of a d flip-flop. The output of the flipflop then shuts down the PWM generator in case of an overcurrent. The flipflop can be reset with a switch, pulling the reset input low.

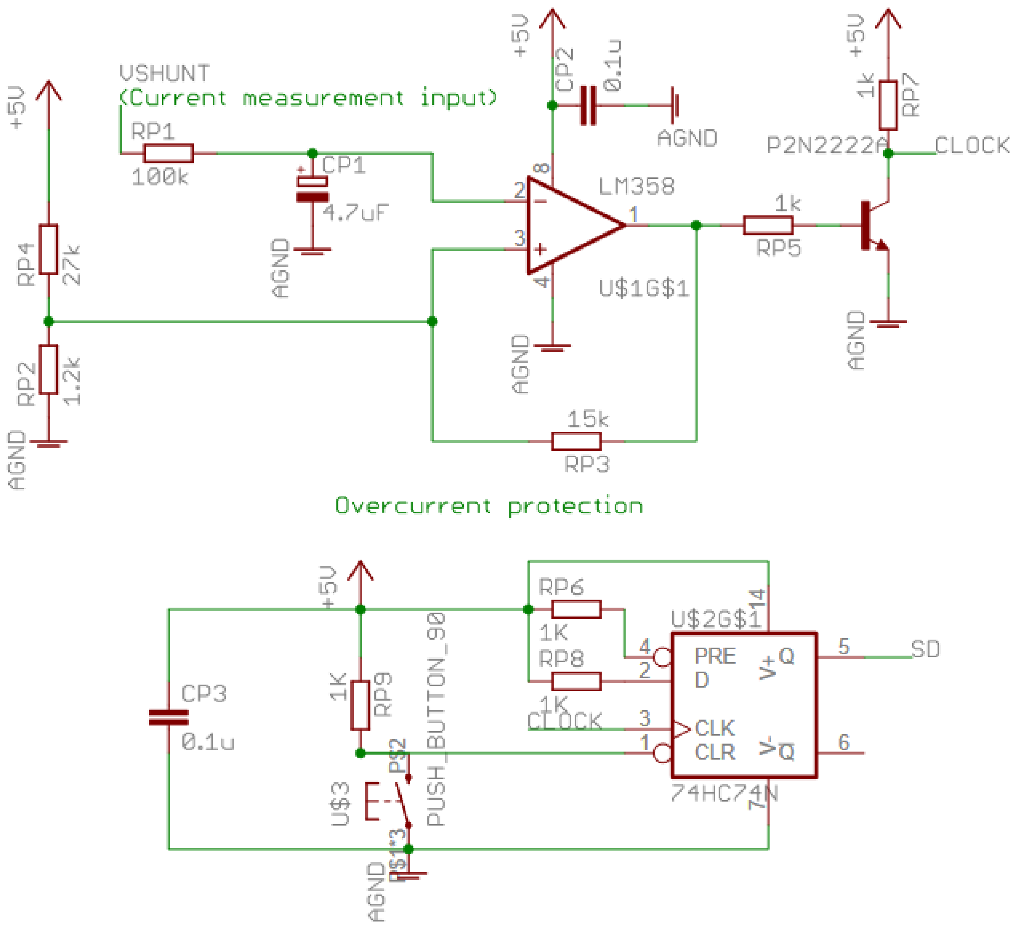

Figure 2.2: overcurrent protection circuit diagram

2.2. Rectifier

The task of the rectifier is to convert the AC signal from the coils back to DC and to protect the load from voltages higher than 20 V.

2.2.1. Full bridge rectifier

The conversion from AC to DC is achieved with a full bridge rectifier circuit. This circuit uses 4 diodes to creates alternating paths depending on a positive or negative voltage, resulting in a DC output to the load. The diodes are all SB540 Schottky rectifier diodes, these diodes have a low power dissipation while staying

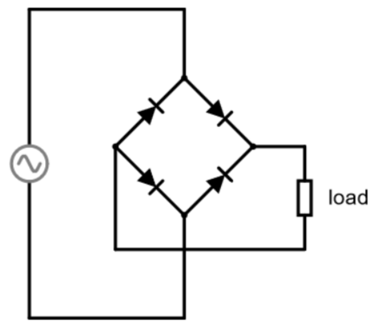

Figure 2.3: rectifier circuit diagram

within the other specifications needed for this application. To ensure safety of the user during operation the complete rectifier is placed inside a protective casing.

2.2.2. Overvoltage buzzer

Because the output voltage may not exceed 20 V, which could be harmful to the load, an overvoltage buzzer is added to the rectifier. This buzzer subcircuit consists of a zener diode with a reverse voltage of 20 V, connected to the base of an NPN transistor. When the output voltage exceeds 20 V, current flows through the zener diode to the base of the transistor, turning the transistor on and closing the current path of the buzzer. The beeping from the buzzer alarms the user that the output voltage is too high.

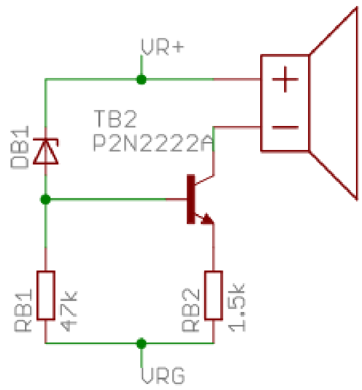

Figure 2.4: overvoltage buzzer circuit diagram

3

Theory & Calculations

The goal with the power transfer system is to have the highest possible power and efficiency. To understand how to achieve this, we must know the relation between the values of components and other variables in the system, like the frequency, so that we can calculate optimal component values and circuit parameters.

3.1. Characteristics of coupled coils

The air core transformer consists of two coils, a large coil on the primary side and a smaller coil on the secondary side. The primary coil should have an inductance of around 100 µH, the secondary coil around 20 µH. Both coils should have a minimum inner diameter of 5 cm and should fit on the provided acrylic plates. Both coils will be made from Litz wire, a special high-frequency wire type which consists of many individually insulated strands bundled together. In this case, the wire consists of 140 strands of 0.1 mm diameter.
The primary coil generates a magnetic field through its center and the secondary coil should capture the most amount of the flux with its center. By making the inner radius of the secondary coil larger than that of the primary coil, the secondary coil will be able to capture more of the flux from the primary coil. With this in mind, the inner diameter of the secondary coil was increased as much as would fit on the acrylic plate, resulting in an inner diameter of about 9.5 cm; see also Figure A.1. Using external calculators [2] [5] the amount of turns and the needed amount of wire can be calculated.

3.2. Theoretical maximization of efficiency

To reach good efficiency, the reactive properties of the coils have to be compensated with capacitors in parallel. To be able to determine the capacitances, we first need to know the frequency, which in turn depends on the mutual inductance, the impedance of the two coils and the resistance of the load.

First, we will determine the mutual inductance M. As explained by the manual [1, p. 18], the mutual inductance of the two coils can be determined by doing two measurements, one with the coils in series and one with the coils in series opposing. For the series configuration, the inductance is given by Eq. 3.1. For the opposing configuration, the inductance is given by Eq. 3.2. Formula 3.3 can be derived by combining Equations 3.1 and 3.2.

$$L_s = L_1 + L_2 + 2M \tag{3.1}$$

$$L_o = L_1 + L_2 - 2M \tag{3.2}$$

$$M = \frac{L_s - L_o}{4} \tag{3.3}$$

Measuring using an RLC meter, L_s was determined to be 158.6 µH, L_o was measured as 86.7 µH and using these values, M was determined to be 17.98 µH.

Using the same RLC meter, the impedance of the primary coil was measured as 177 mΩ, the secondary coil 66.8 mΩ, both at 1 kHz.

Now we can determine the frequency. Section 1.4.2 of the manual[1] explains that maximum transfer efficiency is achieved when Eq. 3.4 holds:

$$R = \omega M \sqrt{\frac{r_2}{r_1}} = 2\pi f M \sqrt{\frac{r_2}{r_1}} \tag{3.4}$$

Where R is the load resistance (10 Ω in this case), r_1 is the resistance of the primary coil and r_2 is the resistance of the primary coil.

As ω does not depend on the individual inductances of the coils or the capacitances used for compensation, it can be used to determine the optimal frequency.

3.2.1. Feasibility of determining the optimal frequency

Using Formula 3.4 and solving for ω gave us a frequency of around 130 kHz, but in practice using this value did not give us good results.

This is because the described way of measuring the mutual inductance M turns out not to be very reliable, and also measuring the resistance/impedance of the coils cannot be done at the operating frequency as the RLC meters only go up to 1 kHz. This means the values of M, r_1 and r_2 we determined cannot be used to effectively determine the optimal operating frequency, so optimization has to be done by trial and error instead of relying on these calculated values too much.

After trying to work with the calculated values and failing, we chose to assume 100 kHz to be a good frequency and used this to calculate the values for the compensation network.

3.3. Compensation

To improve the transfer characteristics of the circuit, we must improve the power factor, which is very low with just the coils as reactive elements.

To do this, capacitors are added in parallel with the coils in order to create a resonant circuit. We know the equation for the resonance frequency of an LC circuit as given by Equation 3.5. In this case, there are two LC circuits: the inverter with its large flat spiral coil and its compensation circuits, and the rectifier with its smaller coil and its compensation circuit. Both circuits must have the same resonance frequency (Eq. 3.6).

$$\omega = 2\pi f = \frac{1}{\sqrt{L_1 C_1}} \tag{3.5}$$

$$= \frac{1}{\sqrt{L_2 C_2}} \tag{3.6}$$

To calculate the value of C from the other values, the equation can be rewritten as:

$$C = \frac{1}{(2\pi f)^2 L} \tag{3.7}$$

L_1 or the primary coil was wound and measured to have an inductance of 100.0 µH. L_2 (the secondary coil) had an inductance of 20.0 µH. Using these values, C_1 was calculated as 25.3 nF and C_2 as 126 nF.

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Test results

The maximum achieved efficiency of the power transfer system was 84.58%. This was with an output power of 28.6 W. The efficiency was the highest on the board, but the power was not as high compared to others (albeit those had lower efficiency numbers). The complete measurement is listed in Table 4.1.

$U_{DC,1}$	19.82 V	DC input voltage
$I_{DC,1}$	1.70 A	DC input current
P_1	33.82 VA	Input power
$U_{DC,2}$	16.99 V	DC output voltage
$I_{DC,2}$	1.68 A	DC output current
P_2	28.60 W	Output power
η	84.58%	Efficiency

Table 4.1: Test results, maximum efficiency; measured with Yokogawa WT500 Power Analyzer

A second test was also performed, now optimizing for the maximum product of power and efficiency. This time, an efficiency of 84.13% with an output power of 40.00 W. This was enough for a second place overall on the board. The second measurement is listed in Table 4.2.

$U_{DC,1}$	19.88 V	DC input voltage
$I_{DC,1}$	2.39 A	DC input current
P_1	47.54 VA	Input power
$U_{DC,2}$	19.98 V	DC output voltage
$I_{DC,2}$	2.00 A	DC output current
P_2	40.00 W	Output power
η	84.13%	Efficiency

Table 4.2: Test results, maximum $P_2 \cdot \eta$ product; measured with Yokogawa WT500 Power Analyzer

These measurements were made while continuously trying to optimize power and efficiency, which was complicated by the number of variables:

- frequency of the inverter
- duty cycle of the inverter
- vertical distance between coils
- horizontal displacement between coils

Finding an optimal balance between these four variables proved challenging but in the end, resulted in the results listed above.

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Conclusion

In the end, we achieved a pretty good result. First place on efficiency alone, second place with the efficiency-power product. Had we had better measurements of the coil impedances and mutual inductance, maybe we would have come to slightly different compensation values and gained some more efficiency and power. The most important goal of the practicals, however, has been reached. We have learned to work in a situation where the numbers *aren't* ideal, and seen a bit of how a good estimate can be made in such a case.

We have also gotten to work with multiple devices and circuits we learned about in the EE2E11 course, gaining some experience with the "field work".

Appendices

A

Supporting Material

Figure A.1: top: secondary coil; bottom: primary coil

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