EE2E11
Electrical Energy Conversion

Student Manual
2023 - 2024

Delft University of Technology

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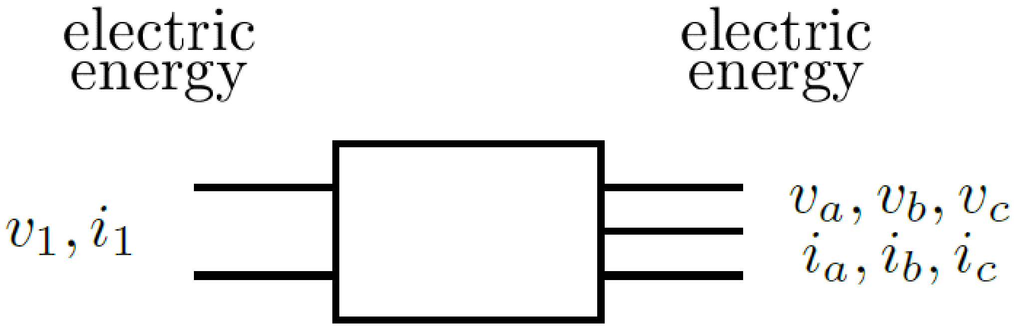

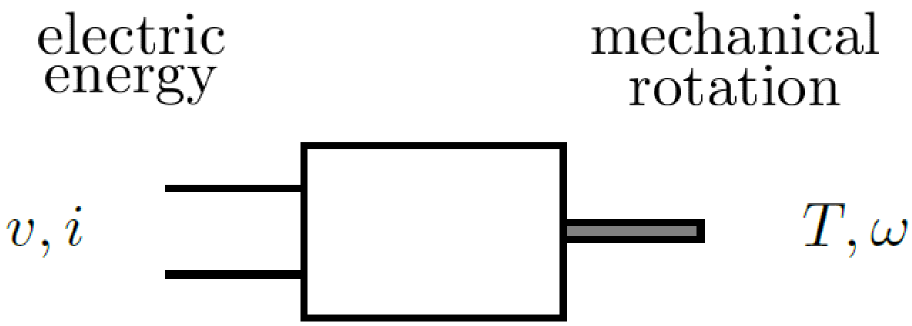

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Part I

Introduction

1 Introduction

Welcome to the practical of the EE2E11 course!

In this quarter, you will apply and integrate the knowledge obtained during the EE2E11 course at the hand of several experiments. Following the main topics of the course, the experiments are grouped in two modules: Power Electronics module (Module 1) and Electrical Drives module (Module 2).

In Module 1, you will build a contactless power transfer system. An important design requirement is maximizing the efficiency.

In Module 2, you will perform experiments on real-life electric machines that you became acquainted with during the course.

This manual starts with a description of the practical, overall objectives, way of working and time schedule.

1.1 Scope

The overall goal of Module 1 is to design and build a power electronics system for contactless power transfer.

The overall goal of Module 2 is to become familiar with physical induction machines and DC machines and measure the torque-speed characteristic of an induction machine.

The duration of the practical is 6 weeks, 5 weeks for the power electronics module and 1 week for the electrical drive module. Each week consists of one half-day in the lab and some self study hours for preparation of the lab assignments and report writing.

1.2 Educational objectives

The overall learning objective of the practical is to apply and integrate the power electronics and electrical machines knowledge in practice. More specifically to:

- Increase skills in building and testing electrical systems, including mechanical aspects, hardware, and measurements.
- Apply the knowledge from the energy conversion course: magnetic circuits, power converters (component choice, topologies, maximising efficiency), electric machines (induction machine, DC machine, torque/speed characteristic).

1.3 Reports

The practical results are to be documented in two reports, one for each module. The reports should document the design choices and design itself (for power electronics module), measurement results and how they compare to the design values. The focus is on your findings and measurement results and the conclusions you drew.

The reports must be handed in before 5.00 PM on the deadline (see Section 1.5). The report for Module 1 and 2 should be uploaded to Brightspace.

The reports are evaluated with pass or fail. You need to get a pass for both reports in order to do the exam.

The assignments are done in sub-groups of two students.

A suggested planning of the assignments is provided, but you can make your own planning as long as you meet the given deadlines in Section 1.5. The student assistants will ask you about your planning.

1.4 Facilities

1.4.1 Lab support

The practical is carried out at the Tellegen Hall. From weeks 2 to 8. The scheduled lab time starts at 8:45 AM and lasts till 12:30 PM.

The following support is available:

- *Student assistants*; student assistants are your primary help. Assistants also check presence and verify your preparation for the lab mornings.
- *Hardware support*; two staff members are responsible for monitoring the process and for problem solving in case the student assistants cannot solve them.
- *Consultants*; for each module consultants are available. They have limited availability (typically 2×2 hours per week). The consultants will also grade your deliverable reports.

1.4.2 List of consultants

- Module 1: Contactless Power Transfer

  Consultant

Dr. Jianning Dong
Email: `J.Dong-4@tudelft.nl`
Tel: 88115
Room: LB 03.630

Hardware support

Joris Koeners, MSc.
Email: `G.J.M.Koeners@tudelft.nl`
Tel: 86225
Room: LB 02.620

Zichen Deng
Email: `Z.Deng-4@tudelft.nl`
Tel:
Room:

Gangwei Zhu, MSc.
Email: `G.Zhu-2@tudelft.nl`
Tel: 88783
Room: LB 03.660

- Module 2: Electrical Drives

  Consultant and hardware support

Harrie Olsthoorn
Email: `h.j.m.olsthoorn@tudelft.nl`
Tel: 86163
Room: LB 02.620
Monday 10.00–12.00; Thursday 10.00–12.00

Joris Koeners, MSc.
Email: `G.J.M.Koeners@tudelft.nl`
Tel: 86225
Room: LB 02.620

Jundong Wang
Email: `J.Wang-16@tudelft.nl`
Tel: 00000
Room:

1.5 Time schedule and deadlines

The practical has 6 scheduled lab mornings in Q1. One morning is reserved for module 2 (separate enrollment is required).

This section shows a suggested time planning regarding assignments and homework, such that you can meet the deadlines.

1.5.1 Module 1: Contactless Power Transfer

1.2 We/Fr	13/15 Sept	Introduction Assignment 1 Design a power electronics converter for contactless power transfer
1.3 We/Fr	20/22 Sept	Assignment 1 (cont'd) — hand in schematic design diagram for verification
1.4 We/Fr	27/29 Sept	Assignment 1 (cont'd)
1.5 We/Fr	4/6 Oct	Assignment 2 Designing and evaluating the air-coupled transformer
1.6 We/Fr	11/13 Oct	Assignment 3 Compensation of the air-coupled transformer
1.7 We/Fr	18/20 Oct	Assignment 3 (cont'd) and performance measurement
1.9 We	1 Nov	**Deadline Deliverable Reports Module 1 and Module 2**

After this module, you have enabled contactless power transfer using coils. The electronics are adjusted to assure optimal power transfer.

1.5.2 Module 2: Electric Drives

Module 2 consists of one experiment, but since the hardware limitations are for a group of 28 students max, 4 mornings have been reserved for this experiment. Students must enroll for one(1) morning. A special booking system will be arranged and announced via Brightspace. You have to arrange the appointments with your partner and yourself within the scheduled time-slots starting from week 3.

1.6 Rules & Regulations

Additional to the rules and regulations of the *Practicumgroep EWI* the following rules and regulations are applicable:

- Students are present at the laboratory at 8.45 AM. Presence is compulsory and will be checked. When you are unable to attend with a good reason, contact Joris Koeners (`G.J.M.Koeners@tudelft.nl`) **before** the lab session. Absence of more than two times will not be allowed, and you will be removed from the practical.
- Preparation for labdays is **necessary** and will be checked by the student assistants. If you do not prepare, you might be removed from the lab.
- You may not work alone in the lab. A staff member must be present.
- You are working with power electronics with high currents, this means that there are several additional safety regulations, see Section 1.7. By not obeying these rules, you are immediately removed from the practical.
- You need to get a pass for both modules in order to pass the practical.

1.7 Safety

- Make sure that all the power sources are off and cannot make contact with your circuit, when you build or adjust a circuit.
- When you build a circuit, let the student assistant check your circuit before powering up.
- Open contacts with a voltage above 42 V is not allowed. Contacts with a higher voltage must be shielded (i.e. placed in a box).
- Make sure your desk is clear when you power up the system.
- Only work with dry hands, and always wear shoes.
- Be careful with jewellery (e.g. rings, necklaces, bracelets, watches), they conduct.
- Metal parts of machines have to be connected to ground.
- When working with rotating machines, be careful with loose clothes, wide clothes or long hair.

- Never touch rotating parts.
- Do not use cables with bad or damaged insulation.
- For the drives experiment, experimental setups may be switched off by students, but only the instructors may switch them on.
- If someone gets an electric shock, turn off the power and call a student assistent or staff member.
- In case of emergency (serious injury to people or objects), press the red emergency button and call a staff member for help.
- If first aid is needed, Ton Slats (room LB01.260) or Martin Schumacher (room LB01.271) can help.
- The emergency phone number with a TU Delft telephone is 112. When you call with your mobile phone, dial 015 27 81226 to be redirected to the TU Delft emergency center.

Always be careful! These regulations are for your own safety and the safety of others. Not obeying the safety regulations will cause immediately removal from the practical!

PART II

MODULE 1: CONTACTLESS POWER TRANSFER

Contactless Power Transfer

MODULE 1

Authors: P. Bauer, J.W. van der Merwe & J. Popovic

In this module you are going to investigate and construct a method of contactless power transfer. You will design a converter (assignment 1) followed by the air coupled transformer (assignment 2). When the system is built, you will optimize it by compensating the transformer (assignment 3). And finally measure and compare the efficiency.

1.1 Introduction

In this module you are going to investigate and construct a method of contactless transferring power. The system implementation can be approached in a couple of steps.

The steps to design the complete system are:

1. Design the DC/AC-inverter
2. Design the AC/DC-rectifier
3. Design, build and test an air-core transformer.
4. Investigate the possibility of transmitting power with the air core transformer.
5. Learn how to compensate the leakage inductances of the air core transformer to enable it to transmit a considerable amount of power.
6. Test and evaluate the complete power transfer system and measure the efficiency.

The steps are split in several assignments. The inverter and rectifier you must design by yourself. In assignment 1 several parts of the inverter are explained. Alternatively you can read extra literature (e.g. papers, books, etc.).

1.2 Assignment 1: Design a power electronics converter for contactless power transfer

Learning objectives The following will be learned and practiced in this assignment:

1. Designing a circuit schematic based on available components (check data-sheets !!)
2. Understanding the function of sub-circuits and connecting them to obtain the full converter (excluding the air coupled transformer).
3. Choosing circuit components to perform a desired function.
4. Assembling and soldering a circuit.
5. Testing a circuit step by step to ensure proper operation.

Deliverable A schematic design of the inverter and rectifier plus a working prototype.

Preparation

- Revisit the power electronics and magnetics parts of EE2E11 reader.
- Datasheets of UC3525 controller IC, IRS2001PBF driver IC, the different switches and diodes.
- Analyze the overcurrent protection subcircuit.

Time duration Two lab sessions for the design and one for building and testing.

1.2.1 Task Description

The task of this assignment is to understand the role of each sub-circuit and connect the sub-circuits into the full DC-DC converter (excluding the air coupled transformer). Choose among provided components where required. Build and solder the full circuit (excluding the air coupled transformer) on the provided PCB.

⚠ **Test the circuits step by step (do not solder the whole circuit at once!).**

1.2.2 Background Information

The power electronic system as shown in Fig. 1.1 consists of three main parts, a DC to AC converter (inverter), a high frequency air coupled transformer and an AC to DC converter (rectifier). Furthermore, there are additional sub-circuits for driving the switches, control and circuit protection (not shown in the figure). You must read the preparation documents and design all three components and its subcircuits.

Think carefully about how you would do this and ask the hardware support or consultant if you have doubts.

⚠ **At this point do not connect the compensation capacitors on the primary and secondary side yet.**

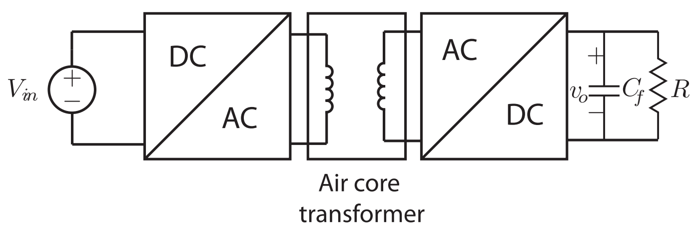


Figure 1.1: The DC-DC converter for contactless power transfer

Gate Driver (IRS2001PBF)

So far in our analysis of power electronic circuits it was assumed that all switches are ideal. This means that they receive some control signal that has no delays and requires no effort to generate. Furthermore ideal switches can switch instantaneously from the on-state to the off-state and vice versa.

Let's first consider the control signal to the transistors. A MOSFET requires a voltage to be generated between the gate and the source terminals, when this voltage is above a certain level the transistor will switch on and below this threshold the transistor will be in the off state. Although it is true that the transistor can operate in the linear region between the fully on and fully off state (as used in linear audio amplifiers) in power electronic circuits transistors are operated in either the fully on or the fully off state to minimize losses. The MOSFET will be in the fully off state when the voltage between the gate and the source is 0 V and in the fully on state when (according to the datasheet) the voltage is higher than 10 V.

The first problem with the generation of this voltage is the fact that although it is relatively easy to generate the voltages for the two switches in the bottom (since their sources are connected to ground) it is much more difficult to do so for the top switches since their source terminals are not connected to ground and can therefore be at any voltage. A special circuit is needed that can deliver and keep a voltage of 15 V between the source and gate terminals of the topside switches under all operating conditions. This includes the worst case scenario where the source terminals are effectively connected to the positive side of the source (since the top switches are turned on).

Although it is possible to build this gate drive circuit using discrete transistors it is much more convenient to use a dedicated gate drive integrated circuit such as IRS2001PBF. The datasheet of this gate drive circuit is found on Brightspace. This gate drive circuit is able to deliver and keep the required voltage under all operating conditions. Furthermore, the gate drive circuit can deliver a current of 350 mA to the gate of the MOSFET transistor.

Switching Times

The second assumption concerning the switching elements was that they switch instantaneously from the on-state to the off-state. Ten years ago this assumption would have been pretty bad even at the low power levels that we are investigating. However, technology improved much during the last years. The transistors that can be used for your circuit can switch from the on-state to the off-state in less than 5 ns. That is pretty quick. Consider that light does not even travel 1 meter in 3 ns! This is however not true for all power electronic switching elements, some of the large switches such as the 6.5 kV and 500 A IGBT (a type of transistor) can have a switching time of between 4 and 7 μs. However, for your circuit it is safe to assume that the switching time is ideal.

You will have several options available for choosing the switches for the inverter circuit. They differ in switching times and losses when conducting. Think about which is the best choice to keep the losses as low as possible and thus efficiency of the whole circuit as high as possible.

There is one other factor to consider and that is the fact that the control signal takes a certain time to travel from the control board to the MOSFET and again a certain time for the MOSFET to react on the signal. It is possible to calculate this time delay by adding the delay times of the MOSFET and the gate driver together. This data is available on the datasheets.

The PWM Generation and Control Circuit

There are several methods to generate the PWM signals for a full bridge converter. The easiest method is shown in Fig. 1.2. Again although it is possible to build a circuit to generate these waveforms using transistors and operational amplifiers it is easier to use a dedicated integrated circuit. We will use UC3525 manufactured by Texas Instruments, again the datasheet for this circuit is found on Brightspace.

1.2.3 Guidelines

You can use the following guidelines to help you achieve the objectives of this assignment:

1. Design all subcircuits and choose the components (switches, diodes). (The focus is on the design and not on the values of the capacitors or resistors, just a quick estimation is enough.)
2. Connect the subcircuits into the full circuit schematic. Design the schematic in such a way that the power segment is separated from the rest of the schematic.

   Discuss and deliver the circuit schematics you designed with the hardware support and/or the consultant and then you will get the inverter and rectifier PCB.

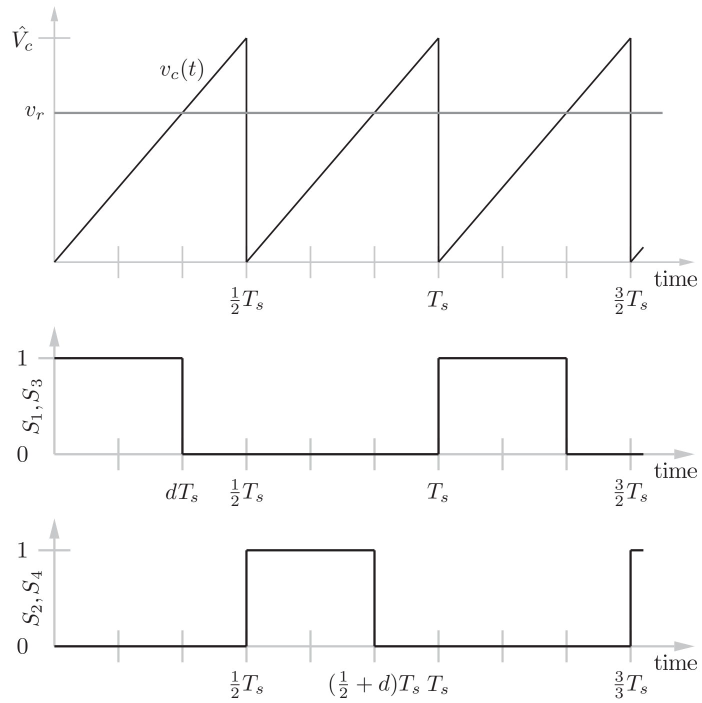


Figure 1.2: Generating the PWM switching signals for the full bridge converter

3. Investigate the behavior of the control circuit: Assemble and solder the control circuit. **Do not solder the gate drive circuits or the MOSFET's into the PCB at this time.** Measure the waveforms of Fig. 1.2 using the oscilloscope. Vary the duty cycle and the switching frequency. Be careful not to brake the variable resistors. How do the values you can obtain correspond to the the datasheet values of the UC3525?

4. Investigate the behavior of the inverter: Assemble and solder the gate drivers and the MOSFET's. Test the inverter **with a resistive load** and measure the waveforms using an oscilloscope. **Do not test the inverter without a load!**

5. Assemble and solder the rectifier circuit. Test the circuit behavior.

1.3 Assignment 2: Designing and Evaluating the Air-Coupled Transformer

Learning objectives The following will be learned and practiced in this assignment:

1. A revisit of the theory of coupled inductors.
2. An alternate measuring technique of the coupled inductor parameters.
3. Using measurement equipment.
4. Analysing and interpreting measurement results.

Deliverable A short report on the experiment.

Preparation

- Revisit the magnetics part of the EE2E11 course reader
- Revisit chapters 8,9 and 10 in *Engineering Circuit Analysis - J. David Irwin*

The design of the two coils (and if possible the winding), as described below, **must be completed before the start of the practicum**. Lengths of Litz wire are available. An in depth understanding of the theory required is also needed **before the start of the practicum**.

Time duration One lab session.

1.3.1 Task Description

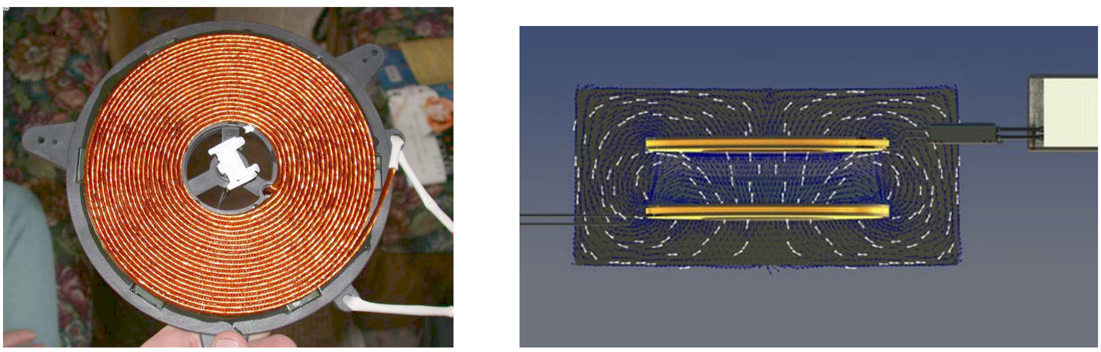
Design and build an air-coupled transformer for the DC-DC converter. Determine the coupling coefficient and other circuit parameters of the air-coupled transformer with various separation distances. Analyse the power transfer characteristics of the air-core transformer system. Evaluate the operation of the DC-DC converter with the air-coupled transformer.

1.3.2 Background Information

For the contactless power transfer an air-core transformer will be used. As with any transformer the system consists of two coupled inductors. However, the main difference is the absence of a well-defined magnetic circuit. This lack of a low-reluctance path for the magnetic flux to couple the primary and secondary windings together results in a magnetically loosely coupled system.

Winding of the Coils

The basic shape of the winding that will be used is shown in Fig. 1.3a. Having this flat shape allows for a little more flexibility in the setup of the contactless power transfer. If the coils are made long and slim instead of flat and wide (as the one shown in Fig. 1.3a) then the alignment of the coils would be more difficult. To illustrate this point, consider Fig. 1.3b, here two coils of the shape of Fig. 1.3a are placed above one another and the distribution of the magnetic flux is superimposed on the image. Although it can be seen that there is a fair amount of flux generated by the coil in the bottom



(a) Basic shape of the contactless power transfer coils. (b) The magnetic field distribution in the air core transformer.

Figure 1.3: A wireless charge coil and its magnetic field.

that does not couple with the coil on top, it can also be seen that the relatively flat shape of the coil helps to capture as much flux as possible.

Each group will design and wind their own coils. First consider the design constraints. The inside diameter of both coils should not be smaller than 5cm. A small inside diameter not only limits the ability of the coil to capture flux but the inner winding also contributes little to the inductance. The total inductance of the larger coil should be in the region of around 100 μH and 20 μH for the smaller.

A special type of high frequency wire, called Litz wire, that consists of many small strands bound together will be supplied for the coils. The total inductance and the length of wire needed can be estimated using the air-core inductance calculator located at `http://www.pronine.ca/spiralcoil.htm` using the parameters of the supplied Litz wire. You can now calculate the size of the inductor for different inner diameters and inductance values.

Measurement methods

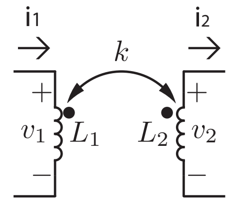


Figure 1.4: Two coupled inductors.

Consider the coupled inductors shown in Fig. 1.4. Let L_1 and L_2 be the self inductance of the two coils and M be the mutual inductance of the two coils. You already know that we can model this circuit with

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} L_1 & -M \\ M & -L_2 \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{1.1}$$

where

$$M = k\sqrt{L_1 L_2}. \tag{1.2}$$

(a) Series aiding connection (b) Series opposing connection

Figure 1.5: Series-aiding and series-opposing connection of coupled inductors

Consider the circuits shown in Fig. 1.5. The inductors are connected in series in both circuits, however, in the one instance the induced voltages are in the same direction while in the other they oppose one another. Measuring the inductance of these circuits as well as the self-inductances of L_1 and L_2 gives enough information to calculate the coupling coefficient.

Lets define L_s to be the total inductance of the two coils connected in the series aiding configuration. Finally, let L_o be the total inductance of the two coils connected in the series opposing configuration.

When the two coils are connected in series (irrespective of whether they are connected in the aiding or opposing configuration) they share the same current, i. If v_1 is the voltage across L_1 and v_2 is the voltage across L_2 the following can be written

$$\mathbf{V_1} = j\omega L_1 \mathbf{I} + j\omega M \mathbf{I} \tag{1.3}$$

$$\mathbf{V_2} = j\omega L_2 \mathbf{I} + j\omega M \mathbf{I} \tag{1.4}$$

when the coils are connected in the series aiding configuration. Using these equations one can calculate the voltage across the two coils when connected in the series aiding configuration, v_a, as

$$\begin{aligned}\mathbf{V_a} &= \mathbf{V_1} + \mathbf{V_2} \\ &= (j\omega L_1\mathbf{I} + j\omega M\mathbf{I}) + (j\omega L_2\mathbf{I} + j\omega M\mathbf{I}) \\ &= j\omega(L_1 + L_2 + 2M)\mathbf{I}. \end{aligned} \tag{1.5}$$

Since the voltage across the the two coils connected in the series aiding configuration is related to the total inductance of the two coils as

$$\mathbf{V_a} = j\omega L_s\mathbf{I} \tag{1.6}$$

you now know that

$$L_s = L_1 + L_2 + 2M. \tag{1.7}$$

You can prove that for the series opposing connection of the two coils the total inductance of the two coils are

$$L_o = L_1 + L_2 - 2M. \tag{1.8}$$

Using these equations you can now calculate the mutual inductance as

$$M = \frac{L_s - L_o}{4} \tag{1.9}$$

and since

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{1.10}$$

you can now calculate the coupling coefficient.

In this discussion you have made a number of simplifying assumptions, most notably you have ignored the winding resistances. Although this simplified model gives you enough information to understand the operation of the system it can not describe all the behaviour of the system, such as the efficiency for example. In the masters course methods of analysing the resistance and describing it as a function of frequency as well as methods to generate detailed models of the magnetic characteristics will be addressed.

Power transfer characteristics of air-coupled transformer and DC-DC converter testing

Due to the loose coupling of the inductors when the air core is used the operation of the DC-DC converter will be quite different. In a full bridge DC-DC converter with a ferrite transformer the coupling between the two coils is very high and one could ignore the transformer power transfer characteristics. Although it is very difficult to analyse the circuit operation in the time domain using the techniques you have used thus far when analysing power electronic converters you can use a sleight of hand to get you out of trouble. Remember that since the switching waveform of the inverter is periodic you can rewrite the time-domain waveform in the frequency domain using the Fourier series. You can now analyse the operation of the transformer circuit and assume that the source is sinusoidal. Although you theoretically have to calculate the currents and voltages for each and every component of the Fourier series to get the full picture of what will happen when you connect the air core transformer to the inverter you can get a very good idea of how well the transformer is working by investigating only the fundamental frequency component. If the transformer is able to deliver a sensible amount of power at the fundamental component chances are good that it will be able to do so with the full waveform.

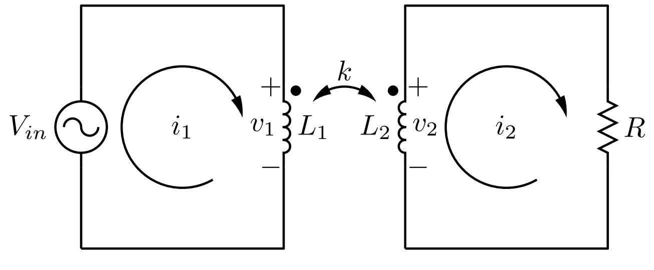


Figure 1.6: Basic coupled inductor power transfer circuit

Consider the coupled inductor circuit shown in Fig. 1.6. Since you are interested in the fundamental component you can assume that the frequency of the source is 100 kHz. Recall that for the coupled inductors you can write the following equation, in the frequency domain,

$$\begin{bmatrix}\mathbf{V_1}\\ \mathbf{V_2}\end{bmatrix} = j\omega \begin{bmatrix}L_1 & -M\\ M & -L_2\end{bmatrix} \begin{bmatrix}\mathbf{I_1}\\ \mathbf{I_2}\end{bmatrix}. \tag{1.11}$$

Using this expression you can write the Kirchhoff voltage loop law equations for the system in Fig. 1.6 as

$$\mathbf{V_{in}} = j\omega L_1\mathbf{I_1} - j\omega M\mathbf{I_2} \tag{1.12}$$

$$\mathbf{I_2}R = -j\omega L_2\mathbf{I_2} + j\omega M\mathbf{I_1} \tag{1.13}$$

If you solve this equation very little power is transmitted to the load resistance if the coupling coefficient is low, say below 0.4. When you include the winding resistances, as in the circuit of Fig. 1.7 the efficiency of the system is very low. You can actually expect that since you can see that the power factor of both systems in Fig. 1.6 and Fig. 1.7 is very low.

$$\mathbf{P}_2 = \frac{V_{in}^2 RL_2/L_1}{R^2/k^2 + \omega^2(k-1/k)^2L_2^2} \tag{1.14}$$

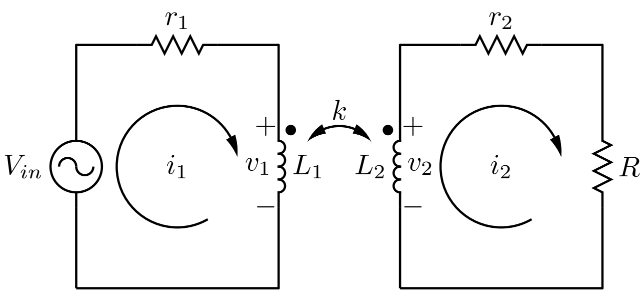


Figure 1.7: Coupled inductor power transfer circuit with winding resistances

1.3.3 Guidelines

You can use the following guidelines to help you achieve the objectives of this assignment:

1. **[Homework]** Design and wind the primary and secondary coil of the air coupled transformer.
2. Measure the parameters of the air coupled transformer for separation distances of 2, 4, and 6 cm.
3. Analyse the power transfer of the circuit. Calculate the power supplied to a load of 10 Ω, the efficiency and the power factor of the circuit. You can assume a 20 V, 100 kHz source. For efficiency calculation you can measure the winding resistances with the LCR meter.
4. Place the air coupled transformer into the DC-DC converter with 2cm distance between the coils. Measure the operational waveforms of the converter, the primary current, secondary voltage, output current. How much power can be delivered to a 10 Ω load?

Due to grounding issues it is not possible to directly measure the voltage across the primary inductor!

1.3.4 What You Should Know

Upon having successfully performed the experiment and studied the required theory, you should be able to answer the following questions:

1. Why is the open and short circuit test not well suited for the air core transformer?

2. Discuss the method used to determine the mutual inductance using the series opposing and series aiding method.
3. How does the leakage and magnetising inductance change with an increase in separation distance? Explain.
4. The problems with delivering power with an uncompensated air core transformer.

You can reflect on some of these questions in the report, where you feel is necessary.

1.4 Assignment 3: Compensation of the Air-Coupled Transformer

Learning objectives The following will be learned and practised in this assignment:

1. Analysis of the resonant compensated transformer circuit.
2. An investigation into possible fault modes.
3. Practical implementation and verification.
4. The operation of over-current system protection and testing the circuit for correct operation.

Deliverable A report on the experiment.

Preparation

- Revisit the power electronics part of the EE2E11 course reader (no. 11 bidirectional DC converters and the "Phase Arms" section of no. 27 AC Drives) as well as the previous practical assignments concerning the power electronic converter
- Revisit chapter 12 in *Engineering Circuit Analysis - J. David Irwin*

All the theory should be well understood and the calculations regarding the compensation capacitor size should be done **before arriving at the practicum.** Various capacitor sizes are available. Determine how you can connect these capacitor into the circuit to get as close as possible to the required capacitance. Try not to connect capacitors with different values in series, they will not share the voltage equally.

Time duration One lab session.

1.4.1 Task Description

A method of compensating the unwanted characteristics of the air-coupled transformer is to be analysed and implemented. When this compensated system is operating under certain conditions the system might fail due to overcurrents. This failure mode and the systems protection circuitry against this error mode is described and must be tested.

The voltage across the compensation capacitors can be high during operation. Take care that you don't accidentally touch the components leads or PCB tracks! Make sure the PCB is in the casing before powering the circuit!

1.4.2 Background Information

In the previous assignment, while analysing the air-coupled transformer, you have seen that the power transfer characteristics of such a transformer are poor, because the power factor of both sides in Fig. 1.7 is very low. In this assignment, you need to look for a solution to this problem.

A common approach to improve the power factor of the inductive circuit is adding compensation capacitors. As shown in Fig. 1.8, capacitors C_1 and C_2 are added in series to the primary and secondary circuit respectively. Similarly to (1.12)-(1.13), by applying the Kirchhoff's law, you can write

$$\mathbf{V_{in}} = j\omega L_1 \mathbf{I}_1 - j\omega M \mathbf{I}_2 + \frac{\mathbf{I}_1}{j\omega C_1} \tag{1.15}$$

$$\mathbf{I}_2 R = -j\omega L_2 \mathbf{I}_2 + j\omega M \mathbf{I}_1 - \frac{\mathbf{I}_2}{j\omega C_2} \tag{1.16}$$

The Thévenin's equivalent impedance of the primary side is calculated from (1.15)-(1.16) as

$$\mathbf{Z_{eq}} = \frac{\mathbf{V}_{in}}{\mathbf{I}_1} = j\left(\omega L_1 - \frac{1}{\omega C_1}\right) + \frac{\omega^2 M^2}{R + j\left(\omega L_2 - \frac{1}{\omega C_2}\right)} \tag{1.17}$$

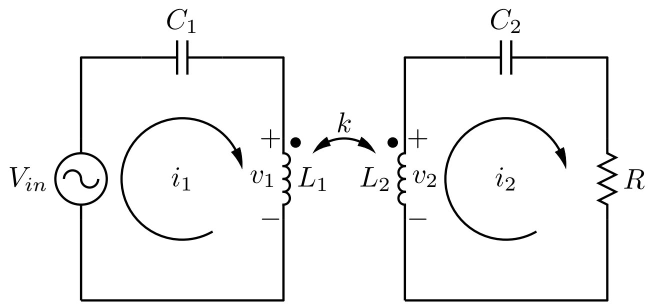


Figure 1.8: Basic compensated coupled inductor power transfer circuit

To transfer maximum power with certain voltage and current, the Thévenin's equivalent impedance should only have real component. Therefore, the two j components in (1.17) both should be 0, which gives

$$\omega = 2\pi f = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{1.18}$$

As you can see, L_1 and L_2 now resonant with C_1 and C_2 respectively at frequency f. Then the primary side Thévenin's equivalent impedance becomes

$$\mathbf{Z_{eq}} = \frac{\mathbf{V}_{in}}{\mathbf{I}_1} = \frac{\omega^2 M^2}{R} \tag{1.19}$$

Now let's calculate the power transfer efficiency of the above fully compensated case, the primary current can be written as

$$I_1 = \left| \frac{\mathbf{V}_{in}}{\mathbf{Z}_{eq}} \right| = \frac{V_{in} R}{\omega^2 M^2} \tag{1.20}$$

Substitute (1.20) and (1.18) into (1.15-1.16) you can get the secondary current is

$$I_2 = \frac{V_{in}}{\omega M} \tag{1.21}$$

The output power is calculated as

$$P_2 = {I_2}^2 R = \frac{V_{in}^2 R}{\omega^2 M^2} \tag{1.22}$$

As we can see from (1.19) to (1.22), when the load and the input voltage are fixed, the current in the coils and the transferred power is determined by the switching frequency and the mutual inductance, hence the power transfer efficiency. In practice the switching frequency is often tuned according to the load to realize a high efficiency power transfer by the so-called ”impedance matching”.

The other problem for the fully compensated case is the misalignment. Consider what would happen if the secondary is removed from the primary or the two coils are heavily misaligned. The mutual inductance M becomes close to 0. According to (1.19) and (1.20), the primary side current will be extremely high since the equivalent impedance is too low. Large current may damage the inverter circuit. Therefore a current sensor is added to the main current path. It measures the current and protects the inverter in case of overcurrent.

1.4.3 Guidelines

You can use the following guidelines to help you achieve the objectives of this assignment:

1. Design the compensation circuit according to figure 1.8.
2. Draw the equivalent circuit, derive the transfer function and analyse it. Calculate the power supplied to a load of 10 Ω, efficiency and power factor of the circuit.

3. Test the compensated transformer in the inverter circuit. Adjust the frequency to the optimal value. Measure the power supplied to the load and compare it to the uncompensated system.

Make sure the circuit board is in the casing before powering on the circuit!

1.4.4 What You Should Know

Upon having successfully performed the experiment and studied the required theory, you should be able to answer the following questions:

1. Why you can estimate how the air core transformer will react when connected to the inverter by investigating its operation with a 100 kHz sinusoidal source.
2. How to compensate an air core transformer and why this works.
3. The potential problem with this compensated system.
4. How the inverter circuit is protected against this fault. You must be able to explain in detail how this works and also be able to give an estimate of the current level where the current protection circuit will trigger.

1.5 Assignment 4: Testing efficiency

Use the setup available to test the efficiency of your circuit under different conditions.

PART III

MODULE 2: ELECTRIC DRIVES

Electric Drives

MODULE 2

Authors: J.A. Ferreira, H. Olsthoorn, J. Dong & J. Koeners

In this experiment you are going to experience the behaviour of real-life induction and DC machines and measure (a part of) the torque-speed characteristic of the induction machine.

Before you are allowed to do the lab work, you have to study the experiments and the theory behind the experiments. After doing the lab work, you have to analyze the measured results, calculate and plot the theoretical torque-speed characteristic of the induction machine, then compare the measured results with the theoretical results. A report has to be be written and submitted to complete the lab work.

2.1 Introduction

In this module we use a DC machine driven by a Siemens siemoreg DC master drive, an induction machine with a three-phase inverter and a Stamford synchronous machine. The machines setup is shown in Figure 2.1.

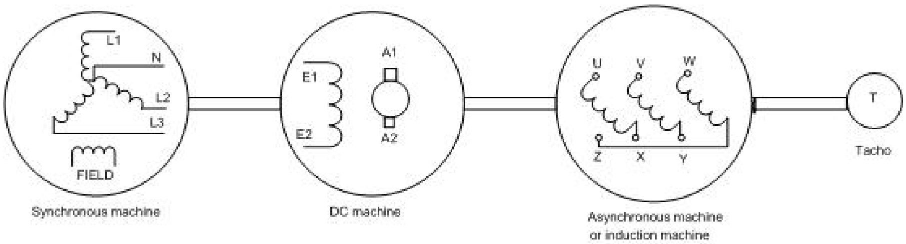


Figure 2.1: Machines setup

The machines are connected on the same shaft. A DC tacho is added for measuring the speed.

The equivalent circuit parameters of the induction machine is shown in Table 2.1.

Table 2.1: Equivalent circuit parameters of the induction machine.

Parameters	Value	Parameters	Value
r_s	9.020 Ω	L_s	54.749 mH
r_r	6.648 Ω	L_r	2.083 mH
L_m	1.043 H		

2.2 Assignment 1: Measurement of Electric Machines

Learning objectives The following will be learned and practiced in this assignment:

1. Gain experience with an actual machine setup.
2. Choosing the machine wiring configuration based on requirements.
3. Measuring the torque-speed characteristic of an induction machine.
4. Calculating and comparing the theoretical torque-speed characteristic with the measured one of an induction machine.

Deliverable A 2-page report includes (see for deadline 1.5.1):

1. A schematic showing the measurement setup;
2. Choice of the induction machine wiring configuration (Δ or Y), and give the motivation;
3. A theoretical torque-speed curve of an induction machine calcualted based on the equivalent circuit shown in Table 2.1;
4. Measured torque-speed points derived from the measurements;
5. Comparison between the theoretical torque-speed curve and the measured points;
6. Causes to mismatch between the theoretical curve and measured points if there are any.

Preparation

- Read the DC Machines and Induction Machines parts of the EE2E11 reader.
- Read this manual thoroughly.

Time duration One lab session.

2.2.1 Task Description

The task of this assignment is to measure a torque-speed characteristic of an induction machine. Determine the correct wiring of the induction machine and the wiring of the measurement setup.

2.2.2 Background Information

Connect the induction machine

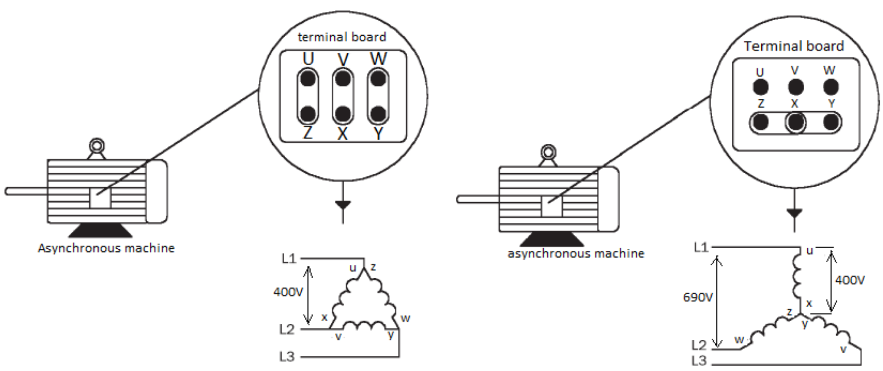


Figure 2.2: Different methods to connect the induction machine using the terminal board.

The induction machine can be wired in different ways. The different methods to connect the induction machine are shown in Fig. 2.2. We should choose the wiring configuration based on the nameplate of the induction machine to be measured, and the specification of the Dutch grid.

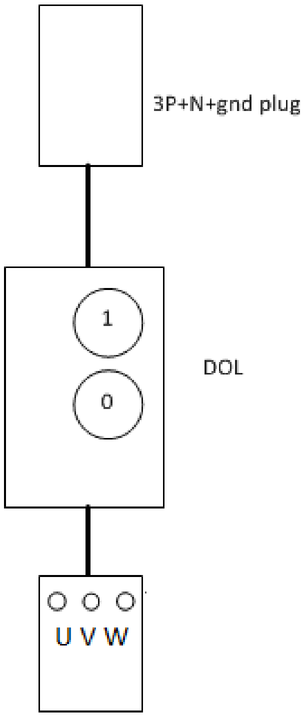


Figure 2.3: Schematic of DOL setup

Connect the induction machine to the grid

We will connect the induction machine to the grid using the DOL (direct on line) switch. For the connections of the DOL see the schematic of Fig. 2.3. For details about the DOL see the document “Use DOL to connect the induction machine to the grid.”

Torque-speed characteristic

The assignment is to measure the torque-speed characteristic of the induction machine. For practical reasons only a part of the speed-torque characteristic must be measured. The section just above and just below the synchronous speed n_s is measured, as indicated in Fig. 2.4.

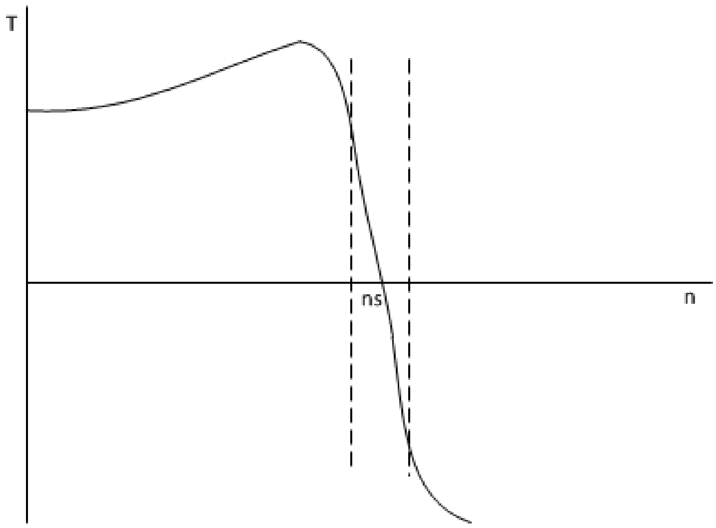


Figure 2.4: Example torque-speed characteristic

2.2.3 Guidelines

You can use the following guidelines to help you achieve the objectives of this assignment:

1. Write down the nameplate data of the machines. (Brand, Type, Nominal stator phase voltage, etc.)
2. We want to connect the induction machine to the grid. Determine from the data on the nameplate if the induction machine has to be connected in star or delta.
3. Draw, based on either a star or delta configuration, the required connections.
4. Connect the induction machine to the grid using the DOL (direct on line) switch.
5. Connect the Chauvin Arnoux power meter to the machine to measure the voltage, current and power.
6. Connect the DC machine to the Siemens DC converter. Connect the rotor connections A1 and A2 and the field connections E1 and E2 of the DC machine to the A1 and A2 and E1 and E2 connections of the drive. Connect the T+ and T- connections of the tacho to the T+ and T- connections of the Siemens DC converter.
7. Place a DC current meter in the rotor circuit of the DC machine and a DC voltage meter parallel on the rotor.
8. Measure the speed with the tacho. On the shaft a DC tachometer is positioned. Connect a DC voltage meter to measure the speed of the shaft. The polarity of the voltage gives the rotation direction of the shaft.
9. Draw the schematic of the setup with all the instruments and wires. **Show your schematic and setup to the consultant before turning on the machines.**
10. Measure a part of the torque-speed characteristic of the induction machine. The DC machine with the Siemens drive is used to drive or load the induction machine.
11. The torque can be determined from the speed and the electrical power. Make sure not to exceed nominal currents.
12. Determine the rotation direction of the induction machine while the Siemens drive is turned off.
13. Determine the rotation direction of the DC machine while the voltage on the induction machine is switched off.
14. *Make sure that the rotation direction of both machines are equal.* The polarity of the DC tacho voltage must be the same.
15. Use the DC machine and the Siemens drive to drive the induction machine at synchronous speed.
16. If the speed is set to synchronous speed, switch on the voltage of the induction machine.
17. Use the DC machine with the Siemens converter to realize some operating points both in motor and in generator operation. The first operating point is at the synchronous speed of the induction machine. The tacho voltage measured at 1500 rpm is the reference tacho voltage. Use a table (example below) to write down the different measurements and calculations for the different points.

n (rpm)	I_{DC} (A)	Udc(V)	Pdc (W)	U_{L12} (V)	I_{L3} (A)	P (W)	PF	T (Nm)
1500rpm Vtach=…V								

18. Calculate the P_{dc} column, which is the power of the DC machine, and the T which is the torque.
19. Sketch the torque-speed characteristic of the induction machine.
20. Complete the report as per the requirements given in section 2.2 and submit it on Brightspace.