Students build their own Switched Mode Power Supplies or how to promote Power Electronics at Universities

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Abstract: The paper presents a concept of labwork in "switched mode power supplies" for students at universities as a supplement to the lecture. Aim of the labwork is to make power electronics more attractive to students, especially to those who originally preferred non power related subjects. Three power circuits have been prepared to be built by the students. These are a step down chopper, a flyback converter and an electronic "DC-DC transformer" based on a series resonant converter. Within the course the students learn to design and build reactive components, they use a smart power IC, insert a voltage control loop and they get an impression of resonant topologies. Thus, the laboratory work covers many different subjects of electrical engineering. The theory is presented in the lecture while most information of the labwork (e.g. datasheets) are available via internet. Up to now the labwork has been carried out 2 times at the FH Köln and the RWTH Aachen. It found high interest among all participating students who enjoyed building their own SMPS circuits. The success of the labwork can also be seen in the fact that many of the students have been encouraged to chose power electronics as a subject for their diplom thesis.

1. Introduction

At the beginning of the nineties, industry in Germany and other European countries cut employment of graduates in electrical engineering drastically. Hence, students had problems to find adequate jobs after finishing university. Since this became public, the number of new students in electrical engineering dropped in the following years. Although the employment situation has changed totally - graduated students now can chose again which company they want to work for – the number of students in electrical engineering is still too low. This is even worse in power engineering because most new students prefer subjects in the telecom, computer or internet area due to the present discussion on information technology IT.
The author of this paper also faced this situation at university and evaluated possibilities to make power electronics more attractive to students. As a result a combined lecture and labwork course in "switched mode power supplies" has been offered to students at the RWTH Aachen and the FH Köln. Due to different requirements the lecture at the RWTH Aachen includes more scientific background while the lecture at the FH Köln has its focus on practical applications. Nevertheless, the labwork is the same for both groups of studends.
In the lab the students have to design and build different SMPS circuits as shown in figure 1. At the end of the work the students can keep the circuits as their own. The labwork found high interest among all students and can be seen as a great success. In order to enable an easy transfer of the idea, this paper presents the concept and summarises the experience of the students' lab work.

Figure 1 Students are building SMPS circuits

2. Switched mode power supplies

Switched mode power supplies SMPS present an important subject of power electronics. They are used for conversion, conditioning and control of electrical power. There is an increasing demand for SMPS in computer, telecom, automotive and domestic applications. Main features of SMPS are high efficiency and high power density. SMPS are important subsystems in various IT products and they are thus of interest for all students.
Today, SMPS are applied in a wide power range between a few Watts and 3kW. The upper limit is determined by the available power to be drawn from the single phase 220V/50Hz mains.
The lower power range is facing a high volume market where the costs of the components are low even for advanced smart power circuits. These components are, thus, best suited for the labwork.

3. Concept of the labwork

For the students' labwork three different power circuits have been prepared. These are:

- a step down chopper
- a flyback converter and
- a series resonant converter

The three converters have been designed considering the following conditions

- low power level < 20W to use small and cheap components
- low voltage level < 50V for safety reasons
- use of one E core type (EF20) with different air-gaps
- use of two coil-former types for EF20
- use of one cheap MOSFET (e.g. IRF630)
- use of 0.2 mm and 0.5 mm solid wire
- use of the smart power IC LM2575_ADJ for the chopper
- use of the current mode controller UC3843 for the flyback topology
- use of the half-bridge FET driver IR2153 for the series resonant converter

The data sheets of the ferrite cores and of all special control ICs are provided on the website of the department to be downloaded by the students. This is possible because all students have easy access to the internet either at home or at university.

selection EF20 core	AL value in nH	Gai gap in mm
Core 1	1300	0
Core 2	330	0.09
Core 3	210	0.17
Core 4	160	0.25
Core 5	100	0.5
cross section area Ae		32 mm²
whole coil window Acu		34 mm²

Table 1 Ferrite cores and coil-former

4. Step down chopper

4.1 Introduction and lecture

The first converter to be built by the students is a simple step down chopper.
Within the lecture the theory of this basic converter has been explained considering both, continuous and discontinuous current flow in the choke.
In the lecture before, the students have already learnt basic design rules of chokes for energy storage. This means the students know how to calculate the current depending flux density of a core and they are able to deal with AL values of commercial ferrite cores.

4.2 Experimental work

The students have to design and build a step down chopper which stabilises the output voltage to a settable value between 5V and 12V. Its whole schematic is presented in figure 2.
The converter will be connected to an isolating 0 ... 40V DC power supply.
It takes advantage of the smart power IC (LM2575 ADJ) from National Semiconductors, which contains the power transistor and all control and protection functions.
For the realisation of the choke the students can select between several EF20 cores with different AL values as shown in table 1. They have also to determine the number of turns of the winding based on solid 0.5mm Cu wire and a winding window of Acu=34mm².
It should result in a choke with an inductance of L = 330 µH. The choke should be able to carry currents up to 1.3 A without being saturated. The free wheel diode of the step down chopper is not integrated in the smart power IC. It has to be chosen independently (e.g. BYV27/200).

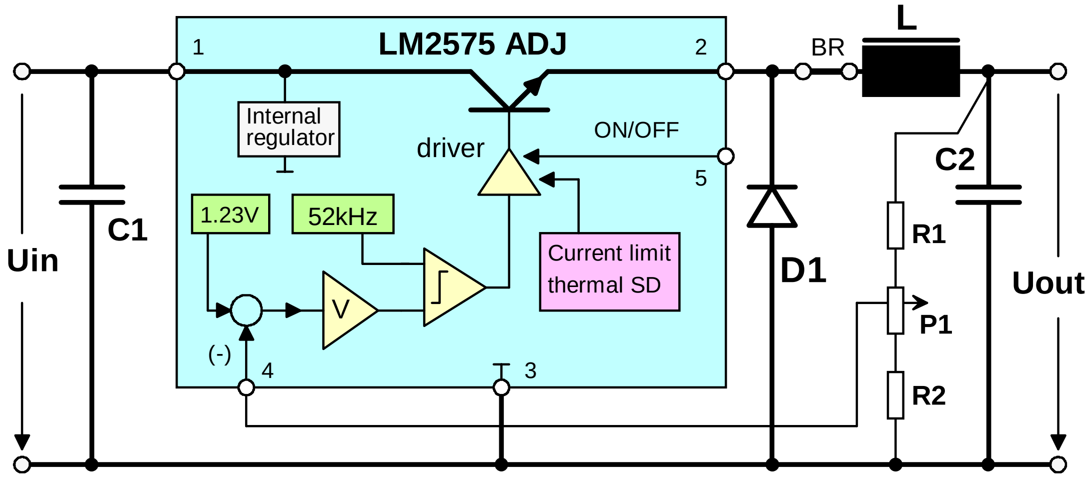


Figure 2 Step down chopper

The ADJ version of the LM2775 allows an adjustable output voltage. The students have to dimension a network R1-P1-R2 which allows to vary the output voltage by the potentiometer P1.
A lot of the labwork can be prepared by the students at home. Apart from the datasheets, provided via internet, the students get some instructions concerning the design. These include a list and a photo of the components (see also fig. 3). Additional information of the corresponding theory are provided by the handouts of the lecture.

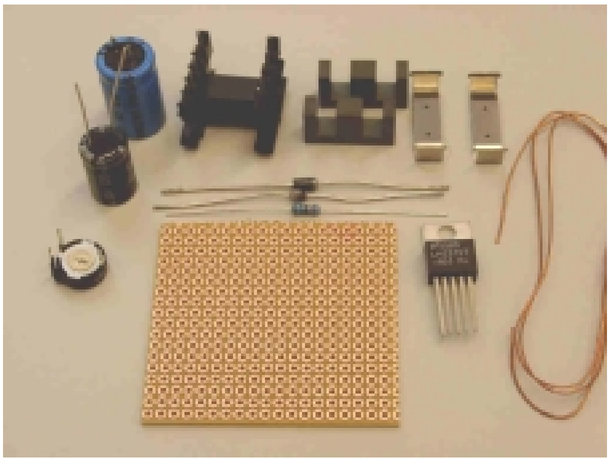


Figure 3 Components needed for the chopper

When the students have studied the data sheets they have to plan the circuit layout. After that, they start their experimental work by building the choke. Subsequently, they mount all components on a small board and connect them. Finally, they test the circuit as shown in figure 4.
To prove, whether the circuit operates properly or not and if not why, the students have to measure the DC voltages at the input and the output as well as the voltage at the free wheel diode and the current in the choke.
For the current measurement a wire loop has to be foreseen and a DC&AC current probe is used. If the circuit operates properly, the voltage and current waves are discussed and the efficiency has to be determined for the nominal current at maximum output voltages.

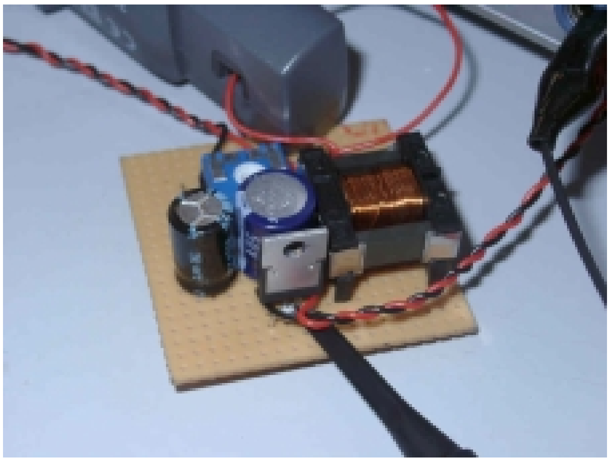


Figure 4 Measurement at the buck converter

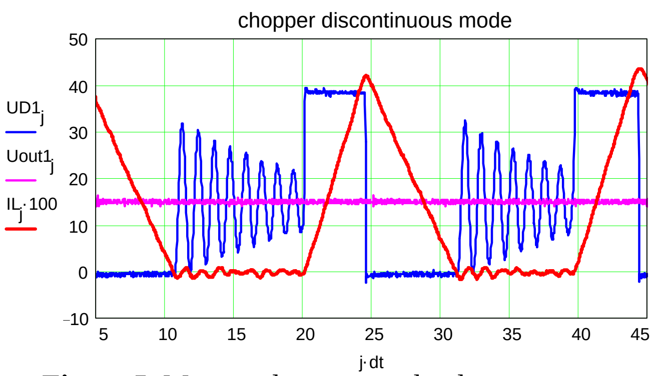


Figure 5 Measured current and voltages

4.3 Experience with the "chopper" labwork

Although some students are successful with their first layout others fail.
One main reason for problems can be found in the choke. Sometimes the students forget to remove the isolation of the wire or they use an E-core without an air-gap. Once this happens, the students have to measure the performance of the choke by an RLC meter after modification. From this experience the students learn, first to check the performance of a subsystem before inserting it in a system. An important point of discussion is the voltage ringing to be seen at the free wheel diode in discontinuous current operation (see also fig. 5). From this measurement and discussion the students get a good impression of the importance of parasitics.
The use of the smart power IC shows a few advantages. It keeps the amount of components low and provides short circuit protection.

5. Flyback converter

5.1 Introduction

The second topology to be built by the students is a flyback converter. It is of special interest for the labwork because of several reasons:

- The flyback converter presents the most simple galvanic isolating DC – DC converter. It can be directly derived from a buck-boost converter by adding secondary windings on the core. On the primary, the flyback converter requires one transistor only while each secondary output can be composed by a diode and a capacitor.

- Flyback converters have been established as the standard SMPS topology in the low power range up to 200W whenever low cost or multiple voltage are required. It is, thus, the preferred power supply solution in almost all TV sets and monitors. Another important flyback application is low power battery charging from the mains, needed for notebooks, handys and shavers.

- The operation of a flyback converter is strongly influenced by parasitic impedances, which has to be considered in the design phase. Figure 6 presents a basic flyback converter including its important parasitic impedances and circuit extensions. It also shows the characteristic voltage and current wave.

The knowledge of the parasitic effects and the way how to handle them is a very important subject for all power electronic engineers.

- The output voltage of a flyback converter is typically stabilised by an advanced current mode controller, which is incorporated in most flyback controller ICs.

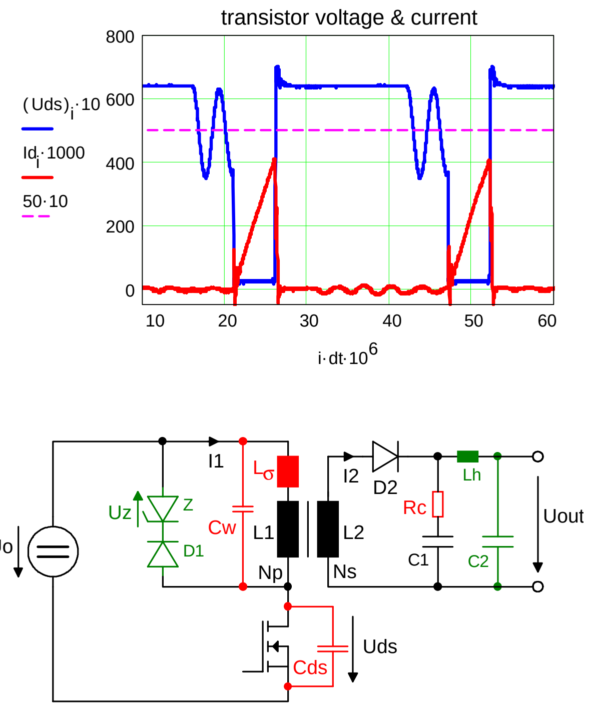


Figure 6 Flyback converter
Top: measurement: Uds and Ic
Bottom: Basic topology with parasitic effects (Lσ, Cw, Cds, Rc) and extra components (D1, Z, Lh, C2)

5.2 Lecture

Within the lecture the flyback converter is introduced as an extension of the buck boost converter. The characteristic current and voltage waves of the discontinuous operation mode are investigated and the current mode controller UC4243 is explained. The simple possibility of multiple output voltages stabilisation is presented as an important advantage of flyback converters.
In a following, the influence of the parasitic impedances is discussed. Here the importance of the transformer leakage inductance as a source for over-voltage and losses is presented. From this investigation, the requirement of a low leakage inductance and the need of a voltage clamp (e.g. zener diode) at the primary winding becomes evident.

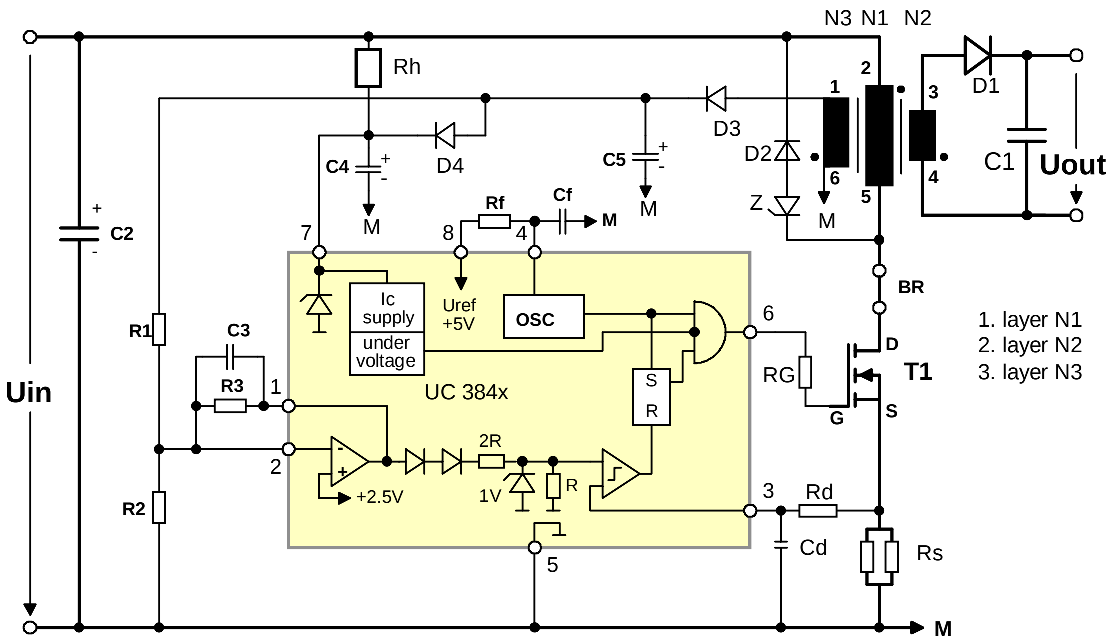


Figure 7 Schematic of the flyback converter

5.3 Labwork

The schematic of the flyback converter is shown in figure 7. It mainly consists of a transformer with 3 windings, a MOSFET, diode capacitor networks and the control IC UC384x

The third winding N3 provides the auxiliary power for the controller and serves as the voltage feed back. This is possible since the turn voltage is the same in all secondary windings when the core energy is released.

The control chip UC384x contains a FET driver, the PWM generator and a current mode controller.

The circuit schematic and most of the data is given to the students. However, depending on the knowledge and experience of the students, some parameters can be left open to be determined at home (e.g. R1, N2, Rf, Z). The students may also be asked to determine the ideal voltage and current waves for the nominal discontinuous operation point at home.

Figure 8 Students are winding transformer-coils

Within the laboratory the students have to build the transformer first (see figure 8). E-cores with different air-gaps and AL-values as well as different wires are provided. The students should know which core to take and how much turns each winding needs. They are advised to take care that

- each winding consists of one layer only separated by thin isolations

- the primary winding is wound first followed by the secondary and the auxiliary winding.

- the inductance of each winding is measured and compared to the value expected theoretically.

- the turn direction of each winding is marked.

Now, the students mount all components on the circuit board and connect them with wire.

After the flyback converter is built, it can be tested. This can best be done by measuring the transistor drain voltage to ground. Figure 9 shows the flyback converter built by a students and the measured drain voltage. By increasing the supply voltage from zero to 50V, the drain voltage is first equal to the supply voltage before it starts to oscillate at a certain voltage level. Subsequently, the operation frequency, the DC voltages and the load depending duty cycle can be proved. The transistor current may be monitored by the voltage drop at the shunt resistor Rs.

For more accurate measurement of the transistor current, a small wire loop "BR" may be added to allow the use of a current probe. Both, the transistor voltage and current should be measured under steady state conditions and either the load current or the input voltage has to be varied. The variation of the input voltage and its immediate influence on the transistor current clearly shows the students the advantage of the current mode controller. Finally the transistor drain voltage can be discussed concerning oscillations caused by parasitic impedances.

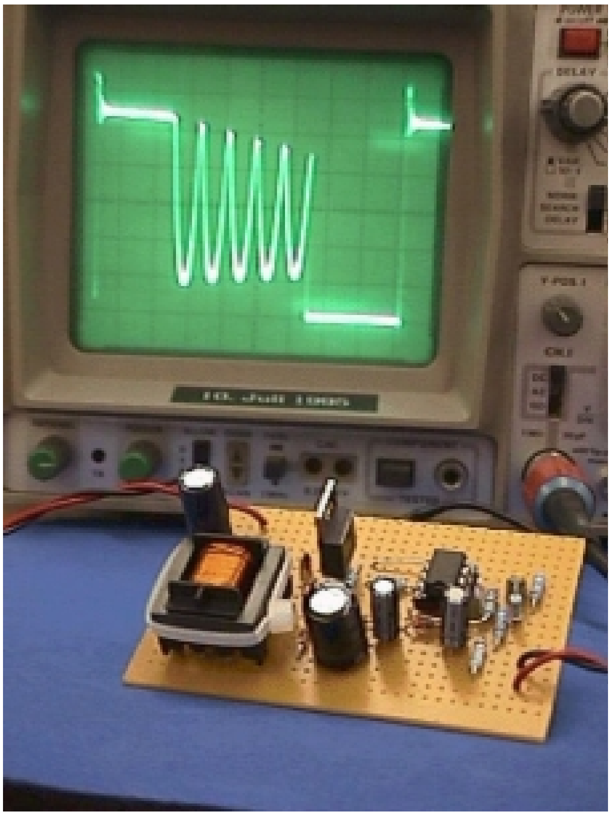


Figure 9 Test of a built flyback converter

5.4 Experience of the "flyback" labwork and possible modifications

After all windings and layer isolations are fixed on the coil-former, the turn direction of the lower winding may be no longer visible. If in the case the students become unsure about the turn direction of the windings they are asked to measure the inductances of each winding and of the series connections of two windings. From these results they should be able to determine both, turn number and relative turn directions of all windings.

The procedure of building the flyback converter by connecting the components individually by single wires takes some time and requires sufficient experimental experience. It turned out that the students, who finished a apprenticeship before starting university, have no problems in building the flyback converter. However, other students without any experimental experience in electronic circuits need much more time than available and in some cases the circuit doesn't work because of wrong or missing connections.
As a consequence, a printed circuit board was designed for the flyback converter which can be used by the students alternatively. This PCB shown in figure 10 reduces the required time substantially. There is still sufficient work for the students since they get no plan where to mount the components . The students can prepare this at home. Another important item of the home preparation is planning where to connect the terminals of the three transformer windings and how to consider the different turn directions.

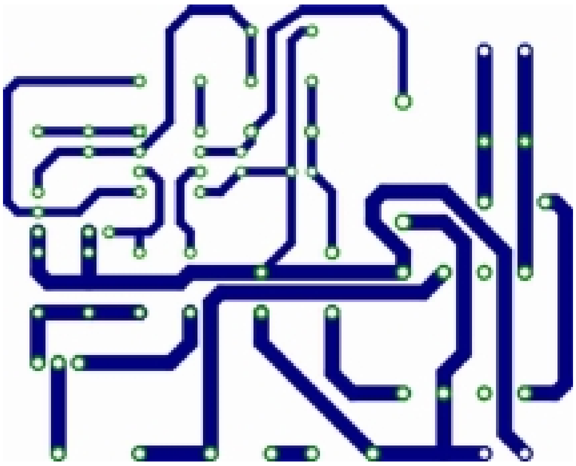


Figure 10 PCB for the flyback converter

6. Series resonant converter

6.1 Introduction

The third topology to be built within the labwork is a resonant converter. This is an important part of the course since resonant operating converters are more and more applied if high power density or low EMI is an issue.
Ideally, resonant converters are designed in such a way that they take advantage of parasitic impedances such as the capacitance of a transistor or the leakage inductance of a transformer. This is also considered by the topology of this labwork.

6.2 Lecture

The converter is first introduced in the lecture by investigating the behaviour of a push pull converter. This hard switching converter is composed by a transistor half-bridge, a centre tapped voltage source, a transformer and a full bridge rectifier with smoothing capacitor (fig. 11).

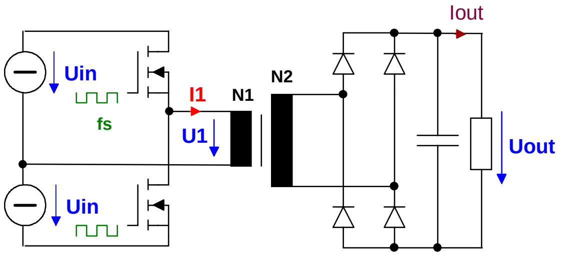
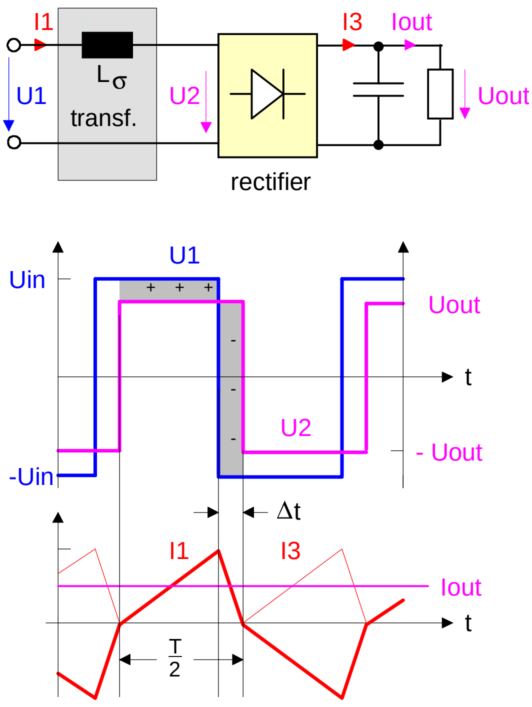


Figure 11 Galvanic isolating push pull converter

For low frequencies (e.g. 50Hz) this topology converts a DC input voltage Uin to a DC output Uout = Uin N2/N1. From previous lectures the students know that the size of the transformer is rather large for a 50Hz frequency. They also know that the transformer size can be substantially reduced if higher frequencies are used.

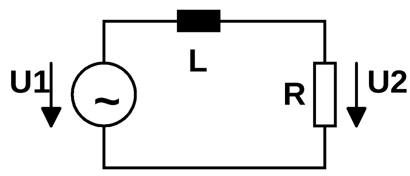


$$Uout = Uin \cdot \sqrt{\left(1 - \frac{8}{Uin} \cdot f \cdot L\sigma \cdot Iout\right)}$$

Figure 12 Analysis of the effect of the leakage inductance at high frequencies

Within the lecture this circuit has been investigated considering a high frequency. This can be done, either by an exact analysis or by a first harmonic calculation. In both cases the transformer can be described by the leakage inductance Lσ only. This assumption is valid for a nominal load and a mutual inductance much larger than the leakage inductance: Lo >> Lσ.

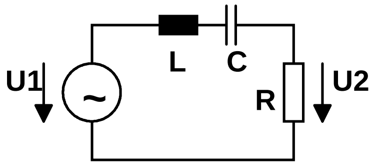
The exact analysis of the circuit is presented in the lecture. The corresponding circuit diagram as well as the resulting formula for the voltage conversion is depicted in figure 12 . The equation clearly shows that the DC output voltage is reduced by the factor $f \cdot L\sigma \cdot I_{OUT}$. This effect can be seen as an inner reactive voltage drop which substantially limits the convertible power.
The same conclusion can be found by using the first harmonic analysis as shown in figure 13.
The used AC calculation is immediately understood by all students since it is part of the basic lectures in electrical engineering.



$$\frac{U2}{U1} = \frac{R}{\sqrt{R^2 + (2\pi \cdot f \cdot L)^2}}$$

Figure 13 1st harmonic analysis of a LR network

At this point, it is very useful to show the students from which geometric parameters the leakage inductance of a transformer is depending of. Moreover, it can be explained how isolation requirements prevent a low leakage inductance.
If the leakage inductance can not be minimised for isolation reasons and if a high operation frequency is desired to reduce the transformer size, another solution has to be found.
Having the simplified schematic of figure 13 in mind, the students probable discover a series capacitor as an ideal solution to the problem
(see also figure 14).



$$\frac{U2}{U1} = \frac{R}{\sqrt{R^2 + \left(2\pi \cdot f \cdot L - \frac{1}{2\pi \cdot f \cdot C}\right)^2}}$$

Figure 14 1st harmonic analysis of a LCR network

The compensating effect of the capacitor can be directly understood by the first harmonic analysis. It becomes also evident that an optimal operation is given if the resonant frequency is identical to the operation frequency.

The exact analysis of the circuit shown in figure 15 leads to an undamped differential equation of order two.

$$\pm(Uin - Uout) = L\sigma \cdot \frac{dI_1}{dt} + \frac{1}{Cs} \cdot \int I_1 \cdot dt$$

From this analysis it becomes evident that the current will be sinusoidal and in phase to the voltage if the operation frequency meets the resonant frequency.

$$fs = fres = \frac{1}{2 \cdot \pi \cdot \sqrt{L\sigma \cdot Cs}}$$

It can also be shown from the equation that the current amplitude automatically adapts to converter power if $\Delta U = Uin - Uout \neq 0$.

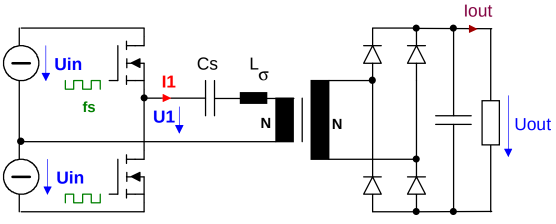


Figure 15 series resonant converter (fs = fres)

6.3 Labwork

The schematic of the series resonant converter is presented in figure 17. The circuit benefits from the half-bridge FET driver IR2153 which includes an oscillator. The same E core type can be used as in the previous circuits. Since energy storage is not necessary no air-gap is needed ($\Delta = 0$).

Similar to the labwork with the flyback converter the students may also take advantage of a prepared printed circuit board PCB shown in figure 16. However, they get no detailed information where to mount the components.

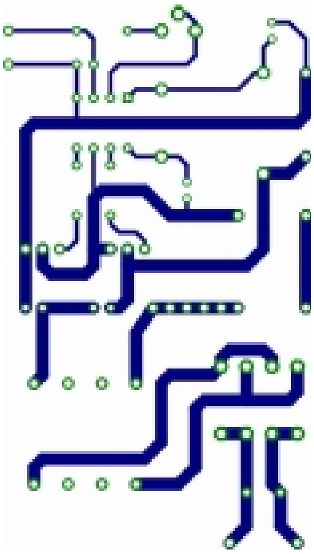


Figure 16 PCB for a series resonant converter

The labwork starts with the realisation of the transformer. Here a coil-former with two adjacent sections for the two windings is used. It provides a very good galvanic isolation between primary and secondary but increases the leakage inductance. The students have to wind the same number of turns for the primary and the secondary winding. It should fill the whole winding area of the coil-former.

When the transformer is finished, the students have to measure the mutual and the leakage inductance from both sites. In the next step, they have to determine a series capacitor Cr which leads to a resonant frequency of about 75kHz.

The last parameters to be selected is the R_t-C_t network which sets the operation frequency of the IC and the converter. By using an additional potentiometer P1 this frequency should be variable between 50kHz and 100KHz.

Now the students can mount all the components on the board. An example of this work is shown in figure 18. When it is finished it has to be tested. Firstly, the gate voltage of the lower transistor can be measured. Its frequency should be near 75kHz and controllable by the potentiometer. If this is the case, the voltage between the half-bridge and ground as well as the primary current should be looked at. For this measurement a typical resistive load can be supplied. At this operation point, the IC frequency has to be set to meet the resonant frequency.

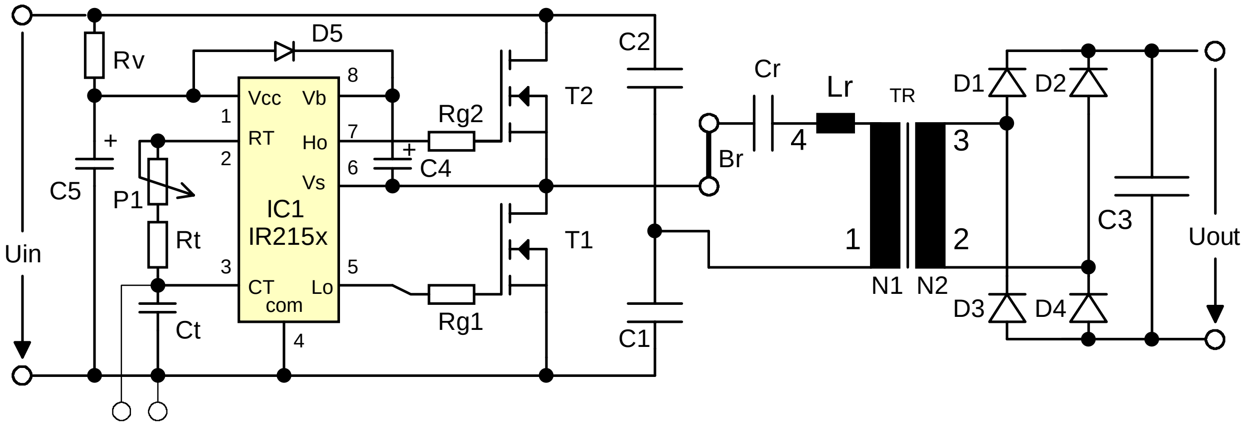


Figure 17 Schematic of the resonant converter

This can be monitored by the voltage and current, which are in phase when the frequencies are equal. This operation point also provides zero current switching ZVS. Now the load current can be varied and it should have no influence, neither on the sinusoidal wave nor on the ZCS operation. Figure 19 presents typical voltage and current waves of the series resonant converter.

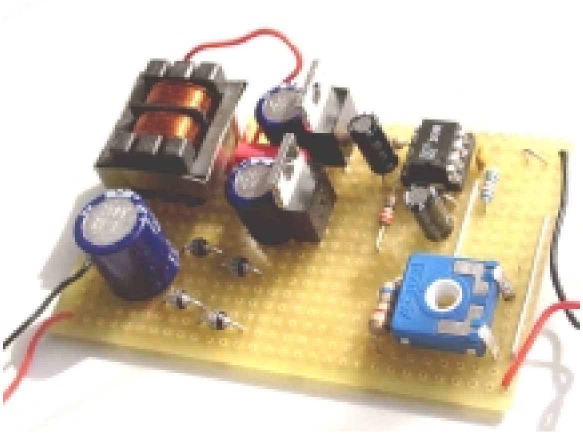


Figure 18 resonant converter built by a student

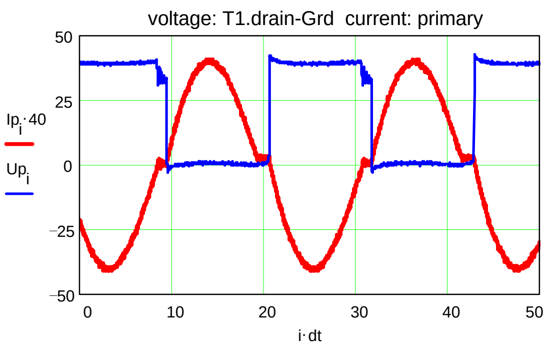


Figure 19 voltage and current measurement

6.4 Experience of the "resonant" labwork and possible modifications

As an additional investigation, the students may measure the output voltage as a function of the output current for a fixed input voltage. The measurement can be repeated at the same circuit after the series capacitor is shorted. The comparison of the two measurements clearly shows the compensating influence of the series capacitor. The effect is even higher at either a higher frequency or a larger leakage inductance.
The circuit provides a very good efficiency which can be influenced by the components used. Best results can be achieved by use of transistors with very low Rdson, by litze wire in the transformer and by schottky diodes at the output.
While the first converter has to be built by each student the last two could also be built in groups with two students. Alternately, one student is responsible for the transformer and the other one mounts the components on the board.

7. Acknowledgement

The author would like to thank the staff of the ISEA at the RWTH Aachen for supporting the labwork and all students who participated.

8. Conclusion

Offering experimental work within a SMPS course is very attractive for students since different disciplines of electrical engineering are covered. Moreover, the labwork is a good opportunity to involve students in power electronics, even students who originally preferred non power related subjects. As a success of the labwork, many of the students, who participated in the course, have been encouraged to chose power electronics as a subject for their diplom thesis.