A Highly Versatile Laboratory Setup for Teaching Basics of Power Electronics in Industry Related Form

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Abstract. This paper presents a laboratory setup for teaching basics of power electronics. The setup is a versatile power electronic system designed in an industry-related form, i.e. with a switching frequency of in the range of 20kHz, a low inductance double sided printed circuit board (PCB) layout, connections via screw terminals and control circuits realized mainly by integrated circuits employed in industrial systems. The setup allows to do experiments and research on a safe 48V DC voltage level. Topics include mains commutated uncontrolled bridge rectifiers, isolated and non isolated DC/DC converter topologies, two- and three-phase DC to AC conversion as well as two- and three-phase AC to DC conversion including power factor correction. The DC to AC conversion could be employed for either driving an AC motor or connecting the system to the AC mains via an isolation transformer.

1 Introduction

Today one possibility of teaching power electronics is to use versatile laboratory setups originally designed for mains frequency converters employing thyristors and diodes. These setups have been adapted with drive circuits to do experiments with MOSFETs, IGBTs or Bipolar Transistors but with a suggestive switching frequency in the range of 100Hz … 1kHz. The advantage of this approach is a very high degree of flexibility. The second possibility for getting familiar with power electronics for the student is to perform a diploma work on a special power electronics topic. This possibility does have the significant drawback, that it is time consuming for the supervising assistant or professor, furthermore, the band of the acquired knowledge is very narrow, but the result can be very close to the needs of the industry. The third possibility is to analyze realized industrial converter systems or the demonstration boards of semiconductor manufacturers. This is a cost intensive way for teaching power electronics, because a lot of different setups have to be installed in the laboratory. An additional main drawback of this way of teaching power electronics is the large amount of different devices the student has to understand.

The approach of the proposed system is to combine the advantages of the different above mentioned concepts of teaching power electronics. There, a single experimental system does include most of the industry relevant power electronic topologies by making connections automatically and/or semi-automatically depending on the demanded topology. The main properties of the laboratory system are:

- realization on a double sided low inductance PCB
- the system does include a heatsink, fans and an auxiliary power supply like an industrial system
- switching frequency f_P = 20kHz
- DC bus voltage is 48V, guaranteeing the safety of the students
- peak current per leg 20A
- connections via screw terminals and not via 4mm laboratory cables
- control circuits realized mainly by industry standard integrated circuits.

The exercises which can be performed by students and/or newcomers in power electronics industry are:

- bridge rectifier circuits with capacitive or inductive smoothing. The inductive smoothing can be performed on the AC or on the DC side of the rectifier by means of an external low frequency (50/60Hz) inductor
- buck, boost converter with optional two-phase interleaved operation
- buck/boost, single-switch and two-switch flyback converter
- forward converter with asymmetric two-switch half and full bridge configuration
- current-fed forward converter
- single- and three- phase power factor correction with continuous and discontinuous conduction mode of operation including output capacitor precharge
- four-quadrant converter (rectifier and inverter mode)
- four-quadrant supply of a DC machine
- three-phase inverter in order to supply a three-phase asynchronous, synchronous or brushless DC machine.

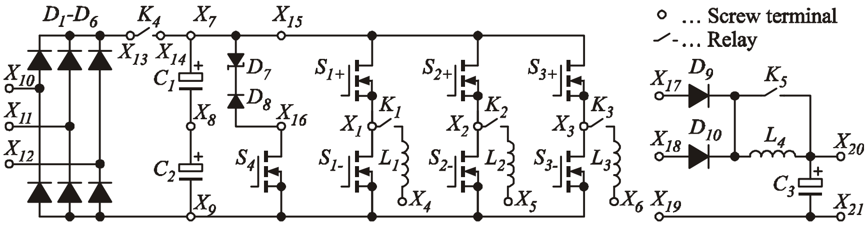

Fig.1: Topology of the laboratory setup for teaching basics of power electronics in industry related form.

The above mentioned exercises give the students the possibility to understand most of the industry relevant topologies in power electronics by means of at least 13 independent laboratory exercises. The exercises can be extended by the development of discrete, microcontroller-based or digital signal processor based control circuits and/or by exercises with the background of controller design and/or stability issues as well as EMI issues. **Section 2** shows the total schematic of the laboratory setup and does give an overview of the applicability of the system. The detailed exercises which can be performed with the laboratory setup are demonstrated in **section 3**. In **section 4** the most important properties of the experimental system are summarized.

2 Topology

Figure 1 shows the topology of the laboratory system for teaching basics of power electronics. The core of the system is formed by three bridge legs S_{i+}, S_{i-} and L_i (i = 1 ... 3) which do realize a synchronous single-phase bi-directional buck converter. The series connected rail capacitors C_1 and C_2 can be charged via the conventional three-phase six-pulse diodes D_1 … D_6 in bridge configuration and do show a center point terminal X_8 in order to make possible a realization of e.g. a symmetric half bridge forward converter. The mains terminals X_{10} … X_{12} do enable the connection to the supplying mains. The relay contacts K_1 ... K_5 do allow to separate certain parts of the system, e.g. to connect a DC machine on terminals X_1 to X_9 = Ground. The relay contacts can be controlled automatically by the microcontroller according to a selected topology or – depending on the micro-program – manually by a push-button by the operator and supervised by the microcontroller. Open relay contacts K_1 ... K_3 do allow to connect a three-phase AC machine on terminals X_1 ... X_3 which could regenerate energy into the DC side capacitors C_1 and C_2 during braking operation. In order to avoid excessive voltages on the rail the braking energy can be dissipated on an external power resistor connected between X_{15} and X_{16} by controlling the power MOSFET S_4. This switch S_4 also could be employed for the buck/boost or the single-switch flyback converter in connection with the output diodes D_9 or D_{10} and the output capacitor C_3 by closing the relay contact K_5 and connecting an external inductor / transformer on terminals X_{15} ... X_{19}. The output circuit consisting of D_9, D_{10}, L_4 and C_3 is also employed for the different forward converter topologies.

3 Exercises

The different exercises which can be performed with the laboratory setup are explained in more detail in the following:

3.1 Bridge Rectifier

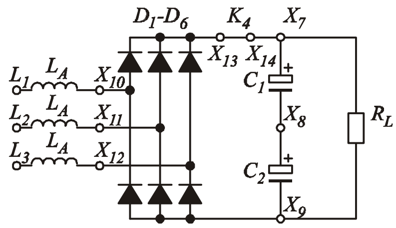

Fig.2: Bridge rectifier with capacitive smoothing and inductors connected in series on the AC side.

In **Fig.2** the passive three-phase bridge rectifier with inductive smoothing of the charge currents by means of AC side external inductors L_A is shown. This basic exercise can be an introduction in the laboratory setup. Relay K_4 needs to be closed and the rail is loaded by a load resistor R_L.

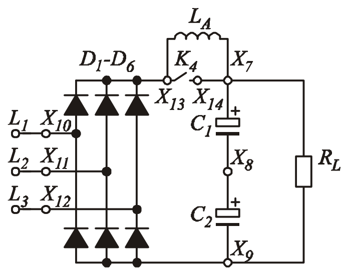

Fig.3: Bridge rectifier with output capacitor and inductive smoothing on the DC side of the rectifier in case of a relatively small inductance value of L_A. This rectifier could also be interpreted as a current source rectifier in case of a large inductance value of L_A.

The shift of the smoothing inductor to the DC side of the rectifier can be investigated with the circuit depicted in **Fig.3** by bridging the open relay K_4 with the auxiliary inductor L_A. With a significant increase of the inductance value of L_A which forces the inductor current to a constant value, i_{LA} = constant, also a rectifier with impressed output current can be investigated.

3.2 Buck and Boost Converter

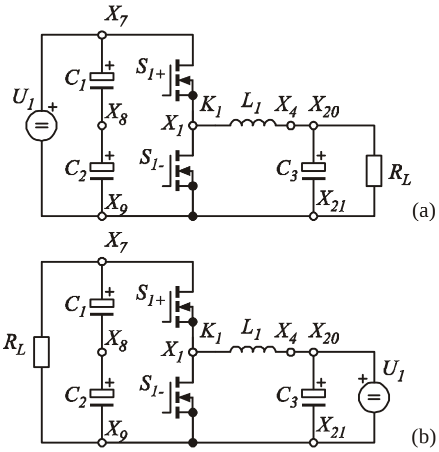

Fig.4: Configuration for Buck (a) and Boost (b) converter. The difference is in the direction of the power flow.

The buck converter can be realized with the proposed laboratory setup as shown in **Fig.4(a)** by employing the first bridge leg S_{1+}, S_{1-}, L_1 and by closing relay K_1. Experiments can be done by forcing the lower switch S_{1-} off and using the intrinsic body diode of the power MOSFET as freewheeling diode or alternatively by performing a synchronous rectification by switching S_{1-} inverse to S_{1+}.

For the boost converter the direction of the power flow needs to be inverted by exchanging the load resistor R_L with the DC voltage source U_1 (cf. **Fig.4(b)**). Again a passive or a synchronous rectification can be done by either forcing now S_{1+} off or switching S_{1+} out of phase to S_{1-}.

Optionally the capacitor C_3 can be wired according to Fig.4 for smoothing the output voltage of the buck converter respectively for supplying of the inductor ripple current for the boost converter.

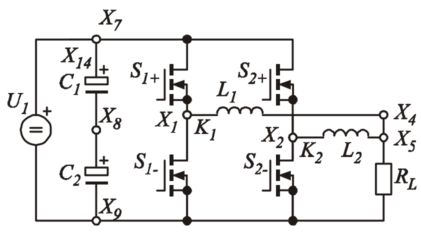

Fig.5: Configuration for buck converter with two-phase operation. The boost converter with two-phase operation can be realized by exchanging of U_1 and R_L (cf. Fig.4).

The buck and the boost converter can be analyzed also for two-phase and interleaved operation by additionally activating the second bridge leg S_{2+}, S_{2-}, L_2, closing the relay contact K_2 and connecting terminals X_4 and X_5 in parallel (cf. **Fig.5** for the buck converter). As described above for Fig.4 also Fig.5 can be adapted for the boost converter by exchanging the DC voltage source U_1 with the load resistor R_L.

3.3 Buck/Boost and Flyback Converter

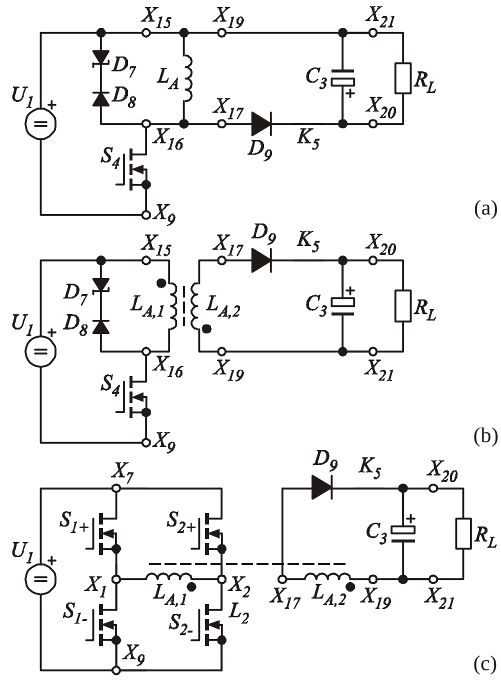

Fig.6: Setup for the buck/boost converter (a), the single-switch flyback converter (b) and the two-switch flyback converter (c).

The buck/boost and the single-switch flyback converter can be realized according to **Fig.6(a)** and **(b)** by employing the MOSFET switch S_4 and the output circuit D_9, C_3 and a closed relay contact K_5. The external buck/boost inductor respectively the transformer for the flyback converter has to be connected to terminals X_{15} / X_{16} ($L_{A,1}$ … primary side) and X_{17} / X_{19} ($L_{A,2}$ … secondary side). According to the flyback topology special attention has to be paid to the winding direction of the transformer windings. The transient turn-off overvoltage of switch S_4 due to the parasitic stray inductance of the transformer L_A is limited by the snubber circuit $D_7 – D_8$.

The two-switch flyback converter (cf. **Fig.6(c)**) has to utilize two bridge legs of the setup S_{ij} (i = 1, 2; j = +, –), open relay contacts K_1 and K_2 (not shown) and the transformer primary winding $L_{A,1}$ connected to terminals X_1 and X_2. MOSFETs S_{2+} and S_{1-} need to be driven simultaneously (in phase) according to the calculated duty cycle. S_{1+} and S_{2-} have to be forced off and the intrinsic body diodes of these MOSFETs do limit the above mentioned transient turn-off overvoltages of the transistors to the value of the rail voltage and the stray energy is recovered back into the rail capacitors. In all three cases the setup has to be supplied by a DC voltage source U_1 connected to terminals X_{15} or X_7 and X_9 and loaded by the external resistor R_L connected to terminals X_{20} and X_{21}.

In all above-mentioned topologies the drive circuits can feature different control methods. In the case at hand a constant switching frequency pulse width modulation control scheme is employed. Additional exercises could be the realization of critical conduction mode control schemes based on the inductor / transformer current.

3.4 Forward Converter

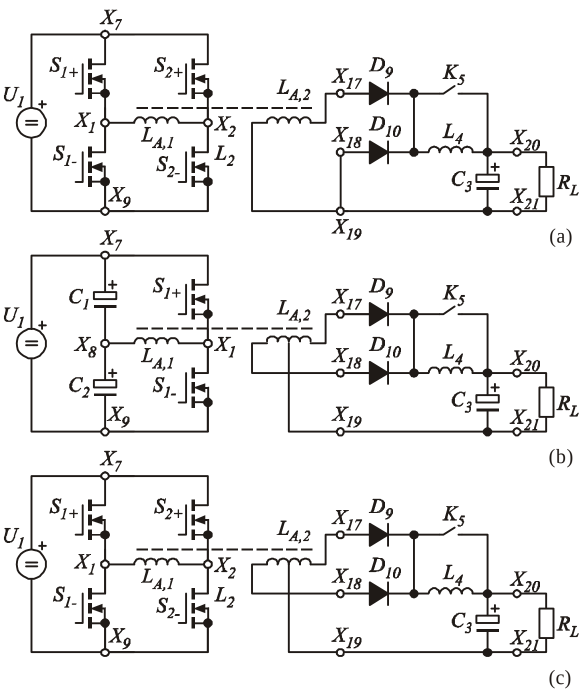

Fig.7: Wiring diagram for different forward converter topologies realized by the laboratory setup: Asymmetric half bridge (a), symmetric half bridge (b) and full bridge (c) forward converter.

The realization of three different forward converter topologies based on the laboratory setup is shown in **Fig.7**. The asymmetric half bridge converter can be realized (cf. Fig.7(a)) by connecting the primary side of the high frequency transformer $L_{A,1}$ to terminals X_1 and X_2 and the secondary side $L_{A,2}$ to terminals X_{17} and X_{19}. Diode D_{10} has to provide a freewheeling path for the output current impressed by inductor L_4 and needs therefore to be connected via X_{18} to X_{19}. The MOSFET switches S_{1-} and S_{2+} need to be driven simultaneously with a maximum duty cycle of d_{max} = 50%. The intrinsic MOSFET diodes S_{1+} and S_{2-} do provide a demagnetization path for the transformer magnetic (ferrite) core.

The symmetric half bridge forward converter can be realized by utilizing the center point of the rail capacitors X_8 and the first bridge leg S_{1+} and S_{1-}. The primary winding $L_{A,1}$ has to be connected to terminals X_1 and X_8 and a center tapped secondary winding $L_{A,2}$ has to be connected to terminals X_{17}, X_{18}, X_{19} according to Fig.7(b). The power MOSFETs S_{1+} and S_{1-} have to be switched 180° out of phase in switching frequency with a defined minimum dead time in order to avoid a rail short circuit.

The full bridge forward converter can be investigated with the setup according to Fig.7(c). In this case the second bridge leg S_{2+} and S_{2-} is employed and switched out of phase to the first bridge leg S_{1+} and S_{1-}. The secondary side of the full bridge converter does also require a center tapped transformer winding connected to X_{17}, X_{18} and X_{19}.

In all three cases the setup has to be supplied by a DC voltage source U_1 connected to terminals X_7 and X_9 and loaded by the external resistor R_L connected to terminals X_{20} and X_{21}.

3.5 Power Factor Correction and Rectifier

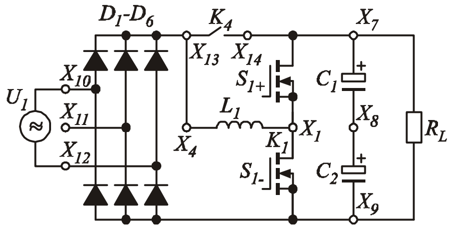

Fig.8: Realization of a single-phase power factor correction (PFC).

A single-phase power factor correction can be done by applying the first bridge leg S_{1+} and S_{1-} as a boost converter (cf. section 3.1), wiring the terminal X_4 to X_{13} and supplying the system by an AC mains voltage source on terminals X_{10}, X_{11} or X_{12} (cf. **Fig.8**). The output capacitors C_1 and C_2 can be precharged by a precharge path using the second bridge leg and doing a resistive connection between terminals X_2 and X_{13} (cf. Fig.1, not shown in Fig.8) with an open relay contact K_1. As soon as the output is charged to the peak value of the supply voltage U_1, the setup can be loaded with R_L and relay K_1 must be closed.

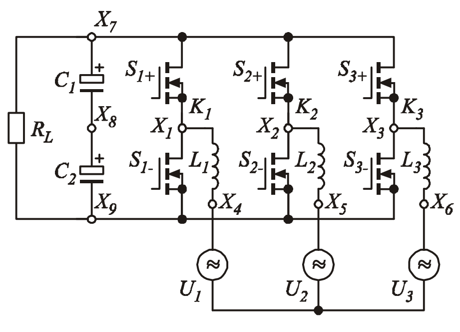

Fig.9: Realization of a three-phase power factor correction (PFC) with the laboratory system.

The realization of a three-phase two-level power factor correction topology with the laboratory system is shown in **Fig.9**. The system does employ the three bridge legs S_{ij}, K_i, L_i (i = 1 … 3, j = +, –) and needs to be connected to the supplying three-phase mains U_1 … U_3 (secondary of a voltage adaptation isolation transformer) via X_4 … X_6. In the sense of simplicity the output capacitor precharge at start-up is not shown in Fig.9, but according to Fig.1 the precharge can be performed with open relay contacts $K_1 \ldots K_3$ by connecting the AC terminals $X_{10} \ldots X_{12}$ of the rectifier bridge $D_1 \ldots D_6$ in parallel to $X_4 \ldots X_6$ and by bridging the relay K_4 via terminals X_{13} and X_{14} by a precharge resistor. After the precharge process has been completed, the relay contacts $K_1 \ldots K_3$ must be closed.

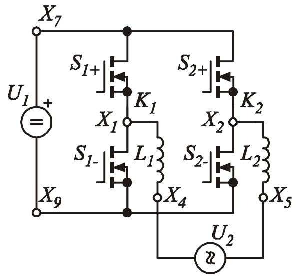

Fig.10: Realization of a single-phase bi-directional rectifier system.

The system shown in Fig.9 does allow a bi-directional flow of energy. By omitting one phase also a single-phase bi-directional rectifier / inverter circuit can be realized with the system at hand (cf. **Fig.10**). In rectifier mode energy is flowing from the AC source U_2 to the DC source U_1 and in inverter mode in the opposite direction.

3.6 Four Quadrant Supply of Electrical Machines

Fig.11(a) shows the four-quadrant supply of a conventional DC machine. By proper switching of the bridge legs variable positive and negative speed and motor and generator mode of the DC machine could be analyzed. In case of a power supply U_1 which is not able to absorb energy during braking (e.g. the conventional rectifier bridge $D_1 \ldots D_6$ is employed) the braking energy has to be dissipated on the external resistor R_L which is controlled by the power MOSFET S_4.

Fig.11(b) demonstrates the inverter configuration for connection of an AC machine. The AC machine can be asynchronous, synchronous or a brushless DC type. The difference in driving the different machines is the control method of the machine voltages and currents.

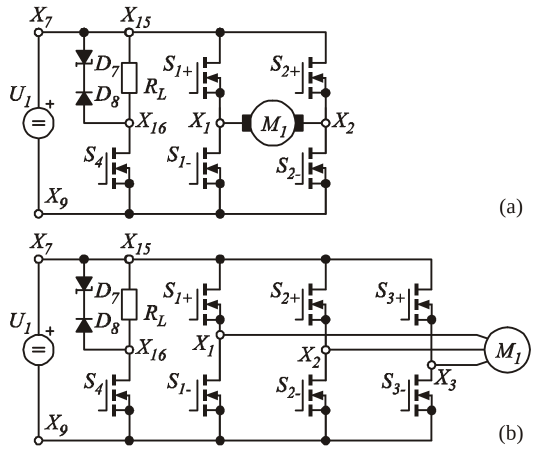

Fig.11: Four-quadrant supply of a DC machine (a) and an AC machine (b) using the proposed laboratory setup.

4 Conclusion

As shown in this paper there is a promising possibility of realizing a versatile laboratory setup which does allow to perform approximately 13 different laboratory exercises on power electronics in higher technical schools, colleges and undergraduate university courses, as planned at the ETH Zurich. The proposed laboratory setup is not only interesting for teaching, but also for training and research on power electronics in the industry. Details of the finished setup will be published at a future conference and on the homepage of Power Electronic Systems Laboratory of the ETH Zurich. The material including detailed descriptions of all examples which could be performed using the setup will be available for other universities and for the industry.

References

[1] **Mohan, N., Undeland, T.M., Robbins, W.P.:** *Power Electronics: Converters, Applications, and Design.* 2nd Edition. John Wiley & Sons.