IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 19 April 2024, accepted 14 May 2024, date of publication 20 May 2024, date of current version 29 May 2024.

*Digital Object Identifier 10.1109/ACCESS.2024.3402822*

TUTORIAL

# Industrial R&D Laboratory for Switch-Mode Power Supplies

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This work was supported in part by BRUSA Elektronik, Munich, Germany; www.brusa.biz.

**ABSTRACT** In literature covering laboratories for switch-mode power supplies (SMPS) the focus was on university ones and learning outcome of their students. And there were almost no publications by authors from industry. Moreover, in a small number of older papers, description of the lab setup or equipment was provided. This paper addressed missing gaps by presenting an industrial laboratory for SMPS. Different aspects like lab structure, organization, procedures, equipment and software resources, calibration and safety, and typical standards used for hardware development, are covered comprehensively. The SMPS lab serves for development of dc-dc converters for commercial project(s) and for research. The developed dc-dc converters are used as auxiliary power supplies (APS) of inductive charging systems. Additional investments in the lab, SMPS related, during period of 1.5 years, were paid-off quickly since the APS was project blocker. Side benefits and outcomes were created by publishing research papers that targeted industry and academia thus bridging the gap between the two. The publications increased company's visibility in academia, created an opportunity for a cooperation project, and served as partial documentation for engineers. It was also shown that investments in equipment and software are not enough. And that one has to invest in knowledge of engineers through buying books, attending seminars, visiting trade fairs, memberships, and subscriptions. Hence, notes on learning of power electronics were given too. Several results of applied research activities are presented to demonstrate lab capabilities. They were characterization of custom-designed magnetic parts at high operating temperatures for operating current range, and solutions for the APS with different flyback topologies. A comparison with few university labs revealed large difference in resources and outcomes in favor of the university ones. But differentiation of our industrial lab to them was covered as well.

**INDEX TERMS** Active-clamped flyback, dc-dc converter, calibration, equipment, laboratory, investment, learning power electronics, magnetic parts, quasi-resonant flyback, safety, switch-mode power supply.

## I. INTRODUCTION

The switch-mode power supplies (SMPS) are important part of everyday modern life and we can find them everywhere around us (e.g. in consumer electronics, household appliances, industrial products…). First lessons on power electronics and SMPS one usually gets in school or at university. In addition, there is a plenty of literature on teaching and learning of theoretical and practical aspects of power converters. After that one shall get first practical knowledge and hands-on experience.

In order to design and test a power converter one needs a laboratory (short: lab) with relevant test and measurement equipment. The power electronic labs can be classified as real, virtual, or remote [1]. The focus in this paper is on the real ones. In general, there are three common approaches to practical learning of power electronics:

- Usage of demo-boards (bought or self-made) [1], [2], [3];
- Usage of flexible or modular experimental platforms [4], [5], [6], [7], [8]; or
- Project/problem based [9], [10], [11], [12].

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott.

However, only in a few papers description of the lab setup and equipment was provided (e.g. [9], [13], [14]). More often the authors would only provide many photos of lab and its equipment without description (e.g. [6], [10], [15], [16], [17], [18]). Moreover, all those papers were focused on B.Sc. and/or M.Sc. students and their learning needs or outcomes. But question: "How industrial lab for research and development of SMPS looks like?" was not answered so far. This is important since how someone shall know what kind of equipment one needs for an industrial lab if never read about or visited one.

Besides [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], and [18], having reviewed additional papers on power electronics labs [19], [20], [21], [22], [23], [24], [25], and on other engineering labs ( [26], [27], [28], [29], [30]), following limitations or gaps were identified:

- Those papers were written by professors or PhD students for BSc and/or MSc students, i.e. there was almost no feedback of authors from industry. The only one paper [31] came from industry, but it was from vendor of the measurement equipment. And it was focused mainly on students' learning in terms of data logging, measurements, and remote communication challenges in a lab setup for power appliances, drives, and power engineering [31]. Those aspects are important, but they are not in scope of this study and that paper was also not focused on the SMPS lab—which is our topic.
- Lab setups and test benches are designed in a way to accompany curriculum on power electronics at universities. And to help students grasp their first hands-on experiences. So lack of insight in industrial laboratories was missing.
- Description of equipment or lab in general was very limited often focusing on one demo-board or universal prototypes that can be used for evaluation of several topologies. Moreover, papers that have a bit more details on the SMPS lab setup and equipment are 20–30 years old (see [9], [13], [14]). Hence, up-to-date info about modern equipment and tools is still missing.
- A description is missing on how industrial SMPS labs are set, where products for series production are developed and tested, or how safety and other work aspects there look like.

The goal of this paper is to present description of HDCIV (higher-dc-input-voltage) SMPS research and development (R&D) industrial lab thus covering mentioned gaps. It aims to be the most comprehensive paper of its kind in literature on SMPS labs so far. And it is a combination of a review-tutorial one with added applied-research results. Note that, although the paper covers SMPS lab of company BRUSA, the majority of its content comes from author's experience.

The term HDCIV was introduced in [32] to avoid confusion with high-voltage (HV) definition per IEC standard [33]. Initially, it was referring to dc voltages $> 450$ V and $< 1500$ V [32], but with papers [34] and [35], we now may state that lower threshold for this definition shall be $> 100$ V and upper one shall be 1000 V. Please note that in automotive sector term high-voltage is referring to dc voltages $> 60$ V and $\leq 1500$ V, and ac rms voltages $> 30$ V and $\leq 1000$ V according to [36]. In rest of the paper such voltages will be denoted as HVa.

The SMPS lab, actually just a bench with accessories, is a part of bigger lab for development and testing of inductive charging systems (ICS) of battery electric vehicles (BEV). Since the ICS lab is one of the key-assets and competitive advantage, its layout and structure cannot be disclosed. Since author established the HDCIV SMPS bench and organized purchase of missing equipment and software for SMPS development that will be focus here. In paper it will be addressed as "lab", "SMPS lab" or "SMPS corner".

The SMPS lab was utilized during development of several dc-dc power converters [32], [34], [35], [37], [38], [39], [40]. Those converters were used as auxiliary power supplies (APS) of the ICS 11 kW, 800 V for BEV [41], [42]. For more info, video demonstrations of ICS operation can be seen in [43] and [44]. During the ICS project execution the SMPS corner was transformed on-the-fly into the shape presented here. More info will be presented in section II-B.

Initially, the goal was only to have possibility to develop an APS in-house. But potential for research activities was recognized soon, resulting in several published papers and two keynote speeches so far. In those papers a balance between academic and industrial contributions is made thus making them useful for people from both academia and industry. Also, it was noticed that BRUSA results on inductive charging of BEV were not noticed in latest review papers on the topic [45], [46], [47]. Therefore, by our publications, a visibility of company was increased in academic world as well. And that resulted in an offer for potential collaboration in EU funded project—which is also kind of return of investment (ROI). Note that in typical industrial labs publication of papers normally is neither wished nor encouraged. But here a compromise was found that research papers serve as a partial documentation for the hardware (HW) team too.

The paper is structured as follows. In chapter II the lab organization, resources, safety, calibration, standards, learning, and investment aspects are covered. The focus of chapter III is on experimental aspects. It presents notes on prototyping, documentation, some procedures, and key achievements with relevant examples. In chapter IV a brief comparison with some university labs is provided. A summary and conclusion will close the paper.

## II. LAB ORGANIZATION AND RESOURCES

In this section we will cover different aspects of lab like organization, physical layout and procedures, equipment and software, calibration, safety, standards used, additional investments for SMPS, and learning of power electronics.

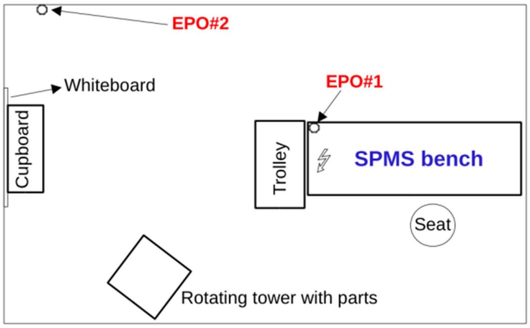
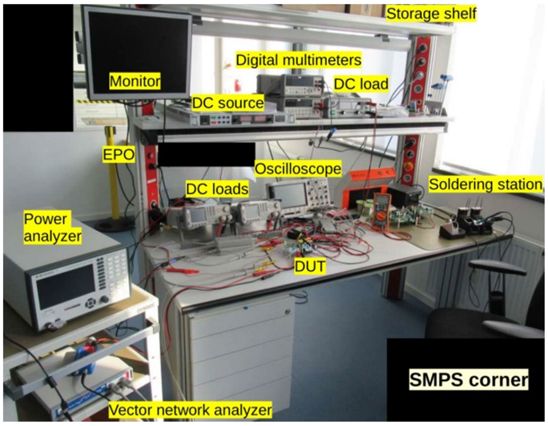


**FIGURE 1.** Sketch of the SMPS corner.



[redacted]

**FIGURE 2.** Photo of the SMPS corner.

### A. STRUCTURE AND ORGANIZATION

The SMPS corner occupies only few m$^2$, and consists of a dedicated bench and a trolley for additional equipment. In Fig. 1 one can see a sketch of the SMPS corner. There we can see the SMPS bench and trolley, positions of EPO (emergency power-off) push-buttons, whiteboard, cupboard with user manuals and safety instructions, and rotating tower with electronic, mechanical, and electromechanical parts. The tower and some other equipment and tools are shared among hardware, software, and test teams. Also, on the SMPS bench one has a monitor in a case that some measurements have to be shown to a bigger group of people. The photo of the SMPS bench with marked devices is shown in Fig. 2.

In general, there are three ways of organization or usage of lab benches in companies:

1) Every engineer/technician has own bench in the lab, or
2) Lab benches are shared between team members,
3) Combination of the two above, i.e. a hybrid approach.

### B. HARDWARE RESOURCES

In this section all test and measurement equipment will be presented. The goal is that readers get a feeling what one needs to have in the lab in order to develop a SMPS that will be used in a mass market later.

The used equipment for SMPS development can be divided into two groups: SMPS only (Table 1) and shared (Table 2 ).

**TABLE 1.** The SMPS dedicated equipment.

| Item | Vendor |
|---|---|
| 4-channel Digital Oscilloscope | Keysight |
| dc source, 1000 V, 1.5 A | Magna Power |
| Precision Power Analyzer, 4-channels | ZES Zimmer |
| DC electronic load 150 W, 2 pcs | Teledyne Lecroy |
| DC electronic load 500 W | EA |
| Dual soldering station | JBC |
| Benchtop multi-meter, 2 pcs | Keysight |
| Handheld multi-meter | Keysight |
| Rogowski current probe | CWT |

**TABLE 2.** The shared equipment.

| Item | Vendor |
|---|---|
| Power Choke Tester, 100 A | ED-K |
| Thermal camera | Keysight |
| Vector network-analyzer | Omicron Lab |
| Thermal chamber | Espec |
| AC source | Chroma |
| DC source 1 kV, 32 kW | Regatron |
| DC electronic load, 2 pcs | Chroma |
| Precision LCR-meter | GW Instek |
| Hi-Pot tester | Chroma |

Note that the lists of equipment in those tables are not exhaustive ones. In addition, in the Table 1 generic accessories like oscilloscope probes (e.g. passive voltage, differential, and current) are not listed since they are common and usually engineers are aware of what is needed. Also, every bench in ICS lab has own set of electrician's tools—which are not listed too.

In Tables 1 and 2 only vendor names and some key features were mentioned. For every specific case, in company or university, the choice of the lab equipment depends on, e.g., developed products, project timeline, available budget, equipment price and its delivery time. Moreover, in our case, one cannot disclose detailed reasoning why the listed devices in Tables 1 and 2 were chosen and not some others.

The listed equipment in Table 1 and Table 2 was not all available from the beginning of the project. At project start only limited number of devices was available and with much higher power than needed. So lab was transformed on-the-fly, and after two years got the look as presented now. For example, before lab transformation we used two big dc electronics loads (few kW) and big dc source (1 kV, 32 kW). They were very noisy and with long cables—which was not the best and not the safest solution or environment to work in. Later they were replaced with smaller ones (see Table 1) thus making work easier and safer (Fig. 2).

With such organized SMPS lab one can develop and test dc-dc power converters up to 1 kV input voltage and few kW of output power. Also development of PFC (power factor corrector) converters with output voltage up to 500 V and output power of 500 W would be possible as well. Also, since SMPS corner is part of the bigger ICS lab, that lab has capabilities to develop inverters as well.

Since in our SMPS one may have voltages up to 1500 V (the SN points in Fig. 6 and Fig. 8) the usage of voltage differential probes of 2 kV was mandatory. Of course, one may use the HV passive probe (2–3.7 kV) as well, but only when SMPS is on a demo-board, i.e. it is floating. Otherwise, in a system usage of such probe with standard oscilloscope would case short-circuit of SMPS (floating) ground to protective earth and cause its damage—which happened to us few times accidentally.

### C. CALIBRATION ASPECTS

Regarding calibration of the equipment one can have different approaches depending on company's budget and strategy for testing or certification. Part of strategy can be risk-analysis of not having some equipment calibrated and resulting measurement errors. Also, calibration planning and/or strategy can depend on project(s) timeline and needs.

In some companies one may calibrate only equipment in the test team while some others may decide that all equipment in R&D department shall be regularly calibrated. The latter case is more expensive, but that gives huge flexibility when it comes to certification or need for a precise measurements. For example, if one wants to do certification tests in-house then all equipment, which one uses for that, shall be calibrated and the calibration data are part of the certification report. And, if time pressure is big, then one has to do many tests in parallel—which means many test devices shall be used at the same time. In addition, as another example, in another company author was a witness when MOSFET drain-voltages were displayed wrongly on oscilloscope due to not calibrated HV passive voltage probes. Therefore calibration of all equipment is always better strategy—although that will cost a lot of money upfront. However, advantages and disadvantages of those approaches one can fully evaluate only in a specific business situation of a company.

The calibration intervals can be annually or every other year, depending on vendors' specifications, and shall be according to [48]. In some cases one may do part of the certification tests in-house—so called "witness tests", where representative of a certification agency is present. And in Germany, for such tests, the test equipment shall be calibrated per DAkkS [49] DIN EN ISO/IEC 17025. Also, one may use different colors on calibration stickers to distinguish them. For example, for calibration per [48] one can use white stickers whilst devices calibrated per [49] can get blue stickers on them. For tracking of calibration status of all equipment one may use spreadsheets, internal databases, or external ones like internet-based test equipment management system [50].

### D. SOFTWARE RESOURCES

Although focus of the paper is on lab hardware it is worth mentioning that one has to invest in software tools as well. First one needs to design something on computer before one can build it and test it. For the R&D activities the following programs are used:

- SIMPLIS [51] (simulations)
- MathCAD® Prime [52](calculations)
- GNU Octave [53] and Libre Office [54] (preparation of figures for reports and publications)
- Microsoft® Excel® (logbook, graphs, and overview of measurements)
- Altium® Designer (schematic and layout, 3D model, production files).
- PLECS® [55] (simulations)
- LTspice® and QSPICE™ (simulations).

The short description of usage areas is provided in brackets. In the above list one can recognize that we combine commercial and free software—which is cost effective. For those interested in free SW for electronics, in paper [56] several free programs are presented with areas of usage.

The SIMPLIS is used only for SMPS whilst other SW is also used by everyone for their own tasks. Since author started using the first three programs, from the list above, only they will be briefly discussed. The SIMPLIS is known as very fast simulator [38], [51] and easy to generate Bode plots for a SMPS [39]. The advantages of MathCAD® Prime are that one can do calculations like on a paper sheet—which is good for documentation. And that they have free version called "MathCAD® Express". With that version one can, e.g., design flyback converters presented in chapter III. The GNU Octave proved itself as a powerful free tool for creation of high-quality professional-looking graphs—which are needed for publications.

### E. SAFETY ASPECTS

Safety of people is very important aspect of a daily work. In Germany, the regulations that covers basic principles of accident prevention [57], [58] are valid for all companies. An employee, i.e. the insured individual, is obliged to "*support the measures taken to prevent occupational accidents, occupational disease and work-related health risks as well as the measures taken to ensure effective first aid*" [57]. Also, "*the insured individual shall report every direct, significant safety and/or health hazard they detect and every defect they detect in protective devices and safety systems immediately to the relevant manager*" [57].

In Germany, maximum effective working time per day is 10 hours, and break (i.e. rest) between two working days shall be minimum 11 hours. The work on Sundays or public holidays in engineering companies is strictly prohibited. In some engineering companies work on Saturdays is allowed, as an exception in critical project phases, only upon announcement in advance and with written permission from management.

Additional standard in Germany that regulates company organization and management, related to requirements for persons working in the field of electrical engineering, is [59]. Furthermore, when working in automotive area with vehicles that have HVa systems, one shall get 2E and 3E certificates per [60] as well to be allowed to work with such systems. Also, some companies may have lab access control so that staff without such certificates cannot enter respective HVa lab areas.

According to [57] it is mandatory for every company to do a risk assessment of their facilities and related working activities. In [61] one can find a short explanation for this process: "*With its preventive approach, the risk assessment forms the basis for effective occupational safety. The aim is to prevent work accidents and work-related health risks as well as to organize work in a humane manner. The risk assessment is an ongoing process consisting of seven steps.*" The seven steps of risk assessment process are [61]:

- Understanding of work areas and activities
- Identification of threats
- Assessment of risks
- Establishment of protective measures
- Execution of those measures
- Checking their effectiveness
- Documenting and updating.

In addition, the following activities or measures shall be considered, when working with HDCIV or HVa circuits, to be allowed to work in a lab:

- One shall get theoretical and practical instructions annually and sign the statement about it.
- In Germany, when working with HV, HVa or HDCIV systems, all lab staff shall have the first aid course passed. Such course provides instructions on usage of an AED (automated external defibrillator) too.
- Never work alone. Minimum two persons are required to be in the lab and not far away from each other. But they do not have to work together on the same bench.
- Wearing of personal protection stuff like ESD coat or ESD shoes (if lab floor is not insulated), safety shoes, goggles, ear protection, etc., is mandatory.
- The work is prohibited if personal protection stuff, test equipment or cables are damaged.
- The work is prohibited if any of the above items is not fulfilled, and the employee has right to refuse to work under such conditions.
- *A tip:* never work in lab when in hurry, tired, stressed, or late in the evening/night.

#### 1) NOTES ON USAGE OF ISOLATION TRANSFORMER FOR POWER SUPPLY OF AN OSCILLOSCOPE

One shall note that there is a common oscilloscope-related misunderstanding. It is about advice to use an isolation transformer for power supply of the oscilloscope—which happened to the author in the past as well. That is wrong and unsafe [62] and author himself had negative experiences from that. Best advice would be that one shall first read the user manual(s) carefully. The oscilloscope manufacturers require users to never interrupt ground of the power supply cord by inserting an isolation transformer since that will create electric shock hazard [63], [64].

**TABLE 3.** List of used standards.

| Standard | Usage |
|---|---|
| IEC 60664-1 [65] | Layout – insulation coordination |
| IEC 60664-3 [66] | Layout – insulation coordination |
| IEC 60664-4 [67] | Layout – insulation coordination |
| UL 840 [68] | Layout – insulation coordination |
| IEC 62477-1 [69] | General safety requirements for PES |
| IEC 61000-4-5 [70] | EMC: Surge immunity test |
| IEC 61508 series [71] | Functional safety |
| IEC 61558-1 [72] | Magnetic components |
| IEC 61558-2-16 [73] | Magnetic components |

As a consequence, for example, insulation system of oscilloscope internal power supply (i.e. transformer) and Y-capacitors might be exposed to different voltage levels—which is dangerous. Also, if one connects a communication cable to a floating oscilloscope, then it is not floating anymore since such cables have earth-referenced returns [62]. Please remember: a device under test (DUT) is a dangerous one—not the measurement equipment [62]. One solution could be usage of battery operated oscilloscope with isolated inputs [62]. More info on the topic with possible lethal scenarios analyzed one can find in [62]. Note that, to the author's best effort, scientific literature on this topic was not found so far. But since life of persons might be endangered with such unsafe practice, it was decided to include sources like [62].

### F. STANDARDS USED FOR HW DEVELOPMENT

In Table 3 the key international standards, which are often used for SMPS development and certification, are listed. Of course, a comprehensive list depends on industry, application, and market, i.e. the country of end usage. Also, names of respective areas where they are used are given in Table 3. One can differentiate four groups: insulation coordination, safety, EMC, and magnetic parts. The hardware developers shall be familiar with those standards and any others that are relevant for a particular application.

### G. NOTES ON LEARNING OF POWER ELECTRONICS

It is important to understand that one needs to continuously invest in knowledge of hardware development engineers. Otherwise investment in lab equipment and software might be in vain. In other words, we need a holistic approach when considering hardware development. Having best equipped lab or CAD software per se cannot solve all the problems. Therefore some thoughts on (practical) learning of power electronics will be provided here.

Typically, the first lessons on power electronics one gets in school or at universities. And few lucky ones may get it in the family as well. Besides that, one needs other aspects of learning—which are based on author's experience—that will be listed here. Of course, the correct (scientific) approach would be to organize a survey among HW developers worldwide then summarize and classify the findings. Since that is a huge work, it may be topic of a future study. For those interested in academic approaches to teaching or learning of power electronics please have a look at references [1], [2], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], and [56].

Seniority of a power electronics engineer is mainly measured on his/her independence during work. For example: whether an engineer is capable to design a power converter from blank sheet without guidance. And to reach that level, in author's humble opinion, after graduation one may need some or all of the listed experiences/exposures:

- Working first 1–2 years in industry just to understand what is going on in industrial life in general or how daily work with SMPS development looks like. The aim is to bridge the gap between school and industrial reality. This and next item are relative since we are all different with different talents, backgrounds, job/lab realities, and so on, hence one cannot make precise statements on that.
- Then one shall work additional 2–3 years, preferably on different projects, to gain more experience thus becoming more independent.
- Be in the right context and business culture.
- Be surrounded with several more experienced engineers to learn from.
- Having a mentor.
- Having own time for further study and self-reflection.
- Be involved in a diversity of projects.
- To have relevant HW equipment and SW tools.
- Be free to make mistakes and even destroy parts (or equipment—which is not desired).
- *Optional and not desired:* to injure oneself or cause an accident.

### H. NOTES ON INVESTMENTS

In our case we had existing bench, some of the equipment (Tables 1 and 2), and some SW available already. The author had to quickly organize purchasing some of additional lab equipment and SW—which was needed for development of the SMPS. Those additional purchases in period of 1.5 years were, for example, power choke tester [74], precision power analyzer, dc source, dc electronic loads, SIMPLIS, MathCAD® Prime, etc. On top of that one could add purchasing of books (e.g. [75], [76]), attending seminars, visiting trade fairs and conferences.

Regarding ROI of the SMPS lab it is impossible to estimate it since part of equipment and SW was already present. And information about that investment was gone because people, who contributed to it, were not with us at the time of writing this article. The developed dc-dc converters were used as APS of the ICS. Since the APS was mandatory part of ICS it was project blocker. One shall be aware that when APS is not working then anything else cannot work too. Therefore, from that perspective, we can state that the investment was repaid so far although we have no specific data for it like time to reach break-even-point or invested money.

There were also intangible (side) benefits through publications. The first one is that company got improved visibility and, for now, an opportunity to apply for an EU-funded project. The second one is that publications serve as part of design documentation for the HW team, guideline for engineering department, and are helping newcomers to faster understand the work as well.

## III. EXPERIMENTATION AND ACHIEVEMENTS

Having reviewed many papers, where authors presented their labs, one could notice that it was common to show few typical experiments that are done in such labs (e.g. [1], [2], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30]). Hence, the same approach is used here. In addition, in this chapter, the readers shall get rough general idea on which approaches were used when it comes to prototyping, documentation, bring-up and troubleshooting activities, and some measurements. Note that the presented thoughts below are universally applicable.

### A. NOTES ON PROTOTYPING

When it comes to prototyping two approaches are most common in industry:

- The board produced and assembled by EMS (engineering manufacturing service) partner; or
- Production of PWB (printed-wiring board) by external company then assembly it by oneself.

There are also known cases where companies or universities could produce simple PWBs in-house [77]. An overview of the developed converters is provided in Table 4. For ACF#1 and ACF#2 the first approach was used whilst for ACF#3 and QRF the second approach was utilized. And author was the one who assembled many of those demo-boards.

Note that PWB is the correct term and not the commonly used PCB (printed-circuit board) since wires are printed—not the circuit [78]. Moreover, the PWB term is also used in [69] and [79].

The off-the-shelf prototype boards were not used since their specification was much different than ours. Our approach was to create small demo-boards (e.g. 9 × 13 cm) with only flyback converter(s) on them. When performance was optimized and the (improved) board was successfully tested, the circuit and/or layout solutions would be implemented in the board which was used in the system. That (physically bigger) board had different development timeline and was not easy to handle on a test-bench. Normally, development engineers need to deliver results fast and on time, e.g. to meet design-freeze deadlines of respective boards. With such approach, the APS related results were available before the design-freeze of that board; thus its development was speeded-up and risks were reduced too.

Moreover, some small prototype circuits, for specific functions, were hand-made by *Adaptacks* [80] technology rather than by using conventional protoboards. The reason was ease of use and possibility to match real layout on a PWB. The only drawback of *Adaptacks* is higher price.

### B. DESIGN DOCUMENTATION AND BOARD RELEASE

Important aspect of development of a power converter is creation of appropriate design documentation and test reports. And typically hardware engineers do not like to do it. In our case we came to a compromise that research papers also serve as partial documentation for HW team as well as general guidelines for the rest of engineering department. In addition, those papers could help junior engineers or newcomers to faster grasp what we are doing.

General approach in industry is as follows. When a board is (preliminary) ready for release, i.e. for production, then one has first to organize an internal design review. The findings from review are tracked and shall be implemented in schematic and layout. After that production files (e.g. Gerber files, pick-and-place file, drill pattern…) will be sent to production site to get their feedback, i.e. DFM (Design for Manufacturing) report. When concerns from the review are implemented, one shall fulfil several checklists and prepare other documents like insulation coordination check or functional circuit-test. When all is done then board can go to the approval committee to get the release, i.e. "green light", for (series) production.

Also, as part of any design process, one shall prepare End-of-Line (EOL) test specifications which will be used for inspection of units on production line. That, together with Hi-Pot test specification, DFMEA (Design Failure Mode and Effect Analysis) report, functional safety (FuSa) analysis [71], Hardware Automotive SPICE® [81], [82], [83], technical cleanliness, and validation of power converters can be a topic of a future study.

### C. POWER-UP PROCEDURE AND TROUBLESHOOTING

When new or revised boards are produced one shall inspect them and perform first power-up, i.e. bring-up test. First, one shall do visual inspection of the boards and make sure that there are no physical damages of the boards or parts, and that correct parts are assembled. After that one can do testing with low voltages (LV) ($< 60$ V dc) and check e.g. PWM signals, measurements, logic signals, etc. If previous two steps are passed, then one may perform tests with higher voltages and power levels (if possible, with a standalone board). Then a report shall be made.

After that one shall repeat the same tests as above, but for two or more boards connected together (depending on functionality). As a last step one shall test the whole system. The findings are presented in standardized documents, i.e. with usage of predefined templates.

We have step-by-step guidelines on how to assembly the system and how to perform bring-up tests (HW and SW). In those instructions there is a procedure, which cannot be disclosed here, on how to test the APS, i.e. SMPS of the system.

### D. CHARACTERIZATION OF CUSTOM MAGNETIC PARTS

In order to evaluate custom-designed magnetic parts, and compare their vendors, one needs to perform several measurements and tests. Moreover, the final tests have to be done in a target converter later. Typical measurements would involve precision LCR-meter to measure (magnetizing) inductance, leakage inductance (for transformers), and dc resistances. In [38] is shown that, with such method, one could wrongly assume that the inductance is constant. What often was missing in literature is the "inductance vs. current" characteristics, $L(I)$. We got such curves by using Power Choke Tester [74]. Such characteristic is important to have since one can see when saturation sets-in and how its slope looks like [39]. And one can see influence of the increased operating temperature on inductance, i.e. how curves $L(I)$ shift to the left side of graphs. More info on the measurement method one can find in [38], [74], and [84]. To the author's best knowledge nobody else was publishing such curves in scientific literature on flyback transformers except in [32], [35], [37], [38], [39], and [40].

Typical procedure, when new samples or parts arrive, is as follows. First, one would do the visual inspection and measure dimensions. Then one shall do measurements with a LCR-meter (e.g. inductances, dc resistances, and leakage inductances of transformers). Measurement of parasitic capacitance was never done. Next, measurements of $L(I)$ with Power Choke Tester at room temperature and, optionally, in thermal chamber at maximum expected temperature of parts' environment would be performed. As a last step, one shall assembly the part in a converter, and then measure its temperature and converter efficiency in normal operation. The results shall be documented in a report.

In Fig. 3 we can see results for flyback coupled-inductors (aka transformer) 600 $\mu$H [34]. In Fig. 4 results for a choke 220 $\mu$H are shown; both at different temperatures and for a range of currents. Both examples are good ones in sense that, with maximum expected operating temperatures and peak currents, inductance drops to "knee" of the characteristics. In such a way one ensures optimal usage of the magnetic material and reduces the costs. The setup photo for above mentioned experiments is shown in Fig. 5. There we can see part of thermal chamber, with extra photo of its display (bottom left), and the Power choke tester (on the right).

### E. DEVELOPED AUXILIARY POWER SUPPLIES

Major task in the SMPS lab so far was development of several auxiliary power supplies (APS) for primary (i.e. ground) side of the ICS. Main prerequisites and features of an APS were discussed in [32] and [42] so will not be repeated here. Resulting achievements of the lab are that several, HDCIV supplied dc-dc converters ($\leq 60$ W), were designed, tested,

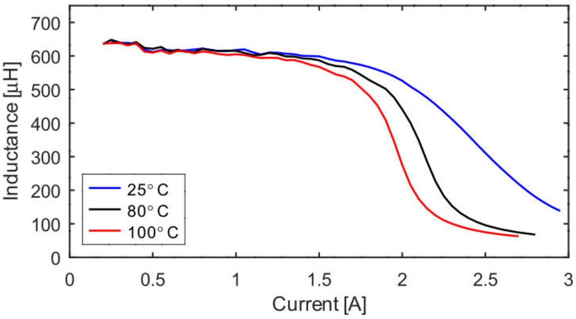


**FIGURE 3.** The *L*(*I*) for flyback transformer 600 $\mu$H.

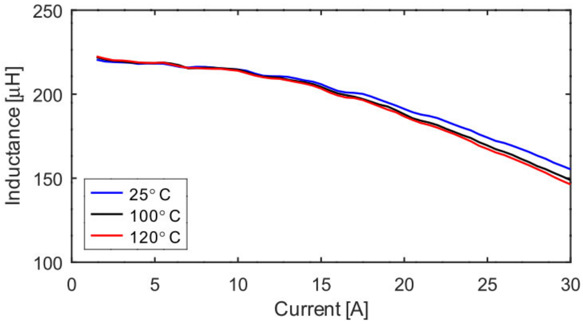


**FIGURE 4.** The *L*(*I*) for a power choke 220 $\mu$H.

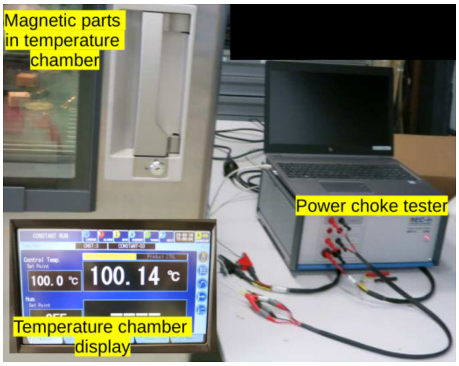

[redacted]

**FIGURE 5.** The setup for measurements at Fig. 3 and Fig. 4.

and optimized. In Table 4 an overview of developed ACF (active-clamped flyback) and QRF (quasi-resonant flyback) dc-dc converters is presented. The reasons for such several solutions lie in our activities during project concept-phase where different architectures for APS were analyzed. More info on that one can find in [34] and [42].

In this section, some results of those converters will be shared for the sake of paper completeness. The results of the ICS 11 kW system are presented in [41] and [42], hence will not be repeated here. The three different ACF dc-dc converters were developed (Table 4 ). And they were analyzed in detail throughout several publications [32], [37], [38], [39], [40], [42]. The specification of ACF#3, which was used in system, is given in Table 5. The solutions with ACF#1 and ACF#2 were abandoned [42] so will not be discussed here.

**TABLE 4.** Overview of the developed converters.

| Item | Control IC | Max dc Input voltage | Output Power |
|---|---|---|---|
| ACF#1 | NCP1568 [85] | 640 V | 13 W |
| ACF#2 | UCC28780 [86] | 640 V | 60 W |
| ACF#3 | NCP1568 [85] | 930 V | 57 W |
| QRF | NCP1340 [87] | 1030 V | 57 W |

**TABLE 5.** Specification of the 57 W ACF DC-DC converter.

| Parameter | Value |
|---|---|
| Input dc voltage (ICS power transfer) | 620–880 V |
| Input dc voltage (ICS stand-by) | 460–640 V |
| Output 1: voltage | + 5.5 V |
| Output 1: current | 1 A |
| Output 2: voltage | + 5.5 V |
| Output 2: current | 2.15 A |
| Output 3: voltage | + 22 V |
| Output 3: current | 1.7 A |
| Output 4/5: voltage | ± 11 V |
| Output 4/5: current | ± 40 mA |
| Output power in ICS stand-by mode | < 10 W |

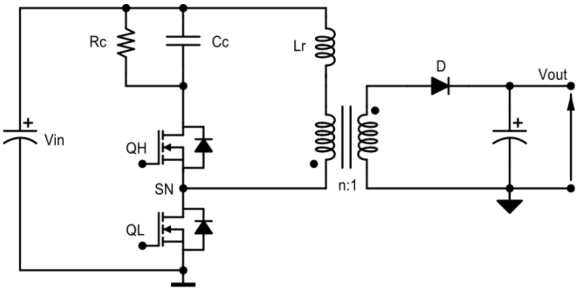


**FIGURE 6.** The generic schematic of an ACF dc-dc converter.

The generic schematic of an ACF dc-dc converter is given in Fig. 6 and implementation photo of the 57 W one (Table 5) is presented in Fig. 7 [32]. The photo of its demo-board is already provided in [37], and is very similar to the implemented version as a result of the process described in section III-A. The ACF 57 W was successfully used in several ICS prototypes and was running seamless for many hours and months so far.

One QRF dc-dc converter 57 W [34],was developed and optimized, after several iterations [35], for the mass production. Its specification is similar to the one in Table 5 with exception that input dc voltage was reduced to 240 V and loads between outputs 1 and 2 were a bit rearranged [34], hence it will not be repeated here. The generic schematic of a QRF dc-dc converter is given in Fig. 8 [34]. And photo of the demo-board is shown in Fig. 9 [34]. The converter proved itself by running seamless for many hours per day, for several months, in a system so far.

Through previous publications it was shown that the QRF is superior to ACF dc-dc converter in terms of costs, occupied

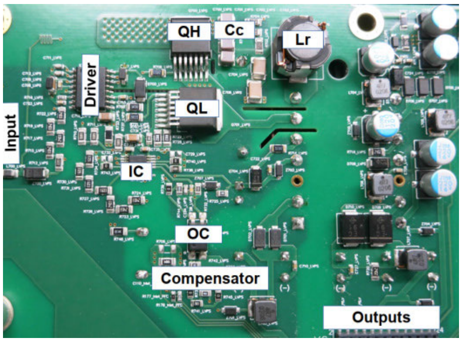


**FIGURE 7.** The implementation photo of the 57 W ACF dc-dc converter.

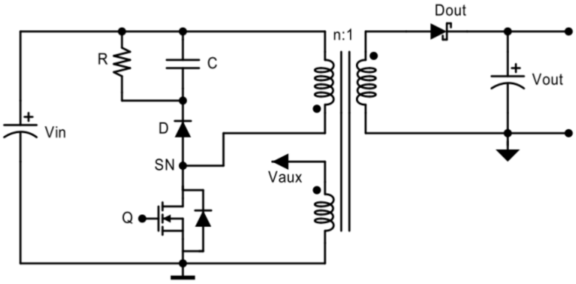


**FIGURE 8.** The generic schematic of a QRF dc-dc converter.

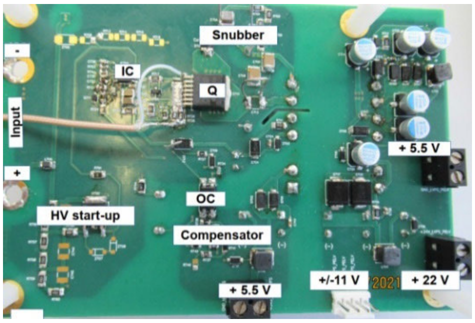


**FIGURE 9.** The demo-board of the 57 W QRF dc-dc converter.

space, complexity, thermal management, and efficiency [32], [34]. The only advantage of an ACF is EMI related one [32], [42]. In addition, here we will present comparisons of losses—which were not published before.

In Fig. 10 one can see the comparison of losses for ACF and QRF converters. The ACF was designed to operate with min input voltage of approx. 450 V. Hence, in Fig. 10 no losses are provided for lower input voltages. The similar transformers (T3-1 and T3-4) were used in both converters, so conclusions below are plausible. The naming of transformers is done as per [34] (*TABLE 4*) or [40] (*TABLE 3*) and there one can see their specification too. The ACF has increased losses that originate from circulation energy [32]. The converters' losses were calculated as subtraction of measured input-power consumption, without load, and (estimated) self-consumption, and (calculated) load on the bleeder resistors. The output

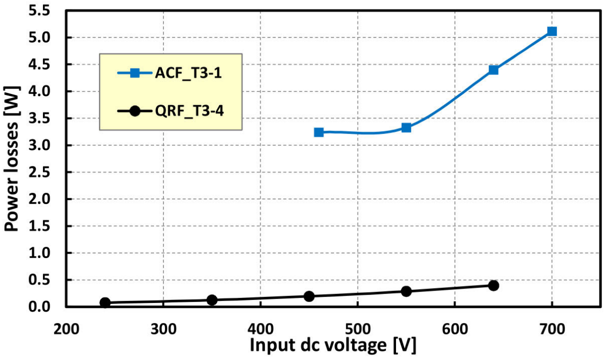


**FIGURE 10.** Comparison of losses between ACF and QRF.

voltages were measured by multi-meter and input power was read from the precision power analyzer.

## IV. COMPARISON TO OTHER LABS

In this chapter we will compare our lab with several university ones [77], [88], [89], [90], [91], [92], [93]. Those labs are chosen at author's discretion, i.e. they were either known or recommended to author. As already mentioned, there is not much available data on such labs or publications on their resources. For example, only lab [88] published a paper [5], but with not enough data on their resources. And on their webpage there is not further data about their equipment. Moreover, only [77] and [91] provided some data on used equipment on their websites, and the rest ones only provided general data like staff info, publications, grants, investments, patents, etc.

Having reviewed websites of above labs following key differences to our lab were identified. They have:

- First goal to support curriculum, i.e. teaching, and then research activities
- Long history (15–30 years)
- Large facilities with several labs
- Many faculties, PhD and master students
- Several research groups lead by prominent professors
- Large investments in equipment (from 100s of thousands USD to millions of USD)
- Annual research grants (from 100s of thousands USD to millions of USD)
- Motivation and business model quite different
- Published papers in range from 10s to 1000s
- Large number of patents granted (10s to 100s)
- Many cooperation partners in industry (10s to 100s).

Besides noble reasons of knowledge sharing or academic career related ones, at university labs publishing of research papers seems like part of their business case, i.e. daily work. Hence, one could assume that they need publications in journals or conferences to increase chances of getting new research grants, and to be able to charge appropriate amount of money later for their services to industrial partners. Then part of that money can be further invested in lab resources and staff thus making them even more powerful.

From above said we see that such labs outperform our SMPS lab in terms of quantity of all resources and outputs. What differentiate us to such university labs is listed below.

- The SMPS lab was established with goal to support running commercial project(s) for OEMs coming from need to have in-house development of SMPS, i.e. to keep know-how in-house. This is important aspect from long-term business perspective.
- We have limited resources and budget, but were still able to produce papers for prestigious journals or magazines.
- First five papers were published with goal that author gets the PhD degree. Later, it was realized that such papers could serve as partial documentation for the HW team, may improve visibility of company, and help to speed-up onboarding of newcomers.
- The published papers are written from perspective of a practicing engineer in industry—i.e. not from an academic one. Thus our papers try to bridge the gap between industry and academia and make them useful for both HW developers and students of power electronics.
- In general, industry needs simple, cheap, and reliable solutions which are not protected by patents. Unfortunately, from author's experience, often a lot of (journal) papers are of no big help to HW developers who need to finish a design on time, i.e. till specific project milestones, with time and cost pressures. And some of those papers may even have errors in mathematical expressions as pointed out in [32], [42], and [94].

## V. SUMMARY AND CONCLUSION

This paper presented an industrial R&D laboratory for HDCIV supplied SMPS. In relevant literature on the topic it was found that the focus was on university labs and learning needs of their students. The missing gaps on industrial SMPS labs are addressed here. The paper covered different aspects like lab structure and organization (e.g. physical layout, procedures, and way of work), equipment and software resources, calibration and safety aspects, and typical standards used. Notes on practical learning of power electronics were given as well. Many aspects covered make this study unique and most comprehensive among published literature on the SMPS labs so far.

The SMPS lab serves for development of dc-dc converters for commercial projects and for research—although the latter was not the initial goal. The publications are done with aim to make them useful for academia and practicing engineers in industry. The developed flyback converters are used as APS of ICS for BEV.

Regarding additional investment in equipment and SW, SMPS related, one cannot talk on ROI in a classical sense since the part of equipment and SW was already present with unknown investment data and the APS was project blocker. Hence, we can state that this additional investment is paid-off so far although we have no specific data for it like time to reach the break-even-point or total amount of the invested money. Side (intangible) benefits were created by publication of research papers. They increased visibility of company in academia, created opportunity for potential public-funded project, and served as partial documentation for colleagues.

It was also stated that investments in equipment and SW are not enough. To fully utilize any lab one has to invest in engineers' knowledge too (e.g. through books, seminars, visiting trade fairs, memberships, and subscriptions). Without skilled and creative people the best equipment and SW are not of much help.

Comparison to several university labs revealed large unbalance in resources (e.g. staff, investments) as well as outputs (e.g. publications, patents) in their favor. But items that differentiate us from them were presented as well.

Several results of this lab are presented to demonstrate its potential and capabilities. The characterization of custom-designed magnetic parts at high operating temperature and full current range was presented first. There one could observe how saturation looks like and how it changes with load and temperature. Second part covered solutions for APS of ICS with ACF and QRF dc-dc converters as topologies of choice. Main features were discussed, and explanation was given on how measurements of losses are executed. Having similar specification and application we saw that the QRF converter has much lower losses than the ACF one. Detailed comparison between the two topologies is provided in [32] and [34].

Limitations of this study are:

- Lack of available data for other (famous) SMPS research labs so comparison with our lab could not be done extensively. Author's wish is that this work stimulates fellow researchers there to publish similar papers, and then do comparison with this one.
- Notes on learning of power electronics are based on author's experience and interaction with many engineers or university staff during his long career. But those observations could be expanded by conducting a survey among development engineers in industry or corporate research centers worldwide. And then publish it.
- The SMPS lab supports running commercial project so not all data could have been revealed. In that sense, not much data on industrialization aspects and validation were presented.

Focus of future research might still be in the area of HDCIV flyback converters and some industrialization aspects as listed in section III-B.

## NOMENCLATURE

| | |
|---|---|
| ACF | Active-clamped flyback. |
| AED | Automated external defibrillator. |
| APS | Auxiliary power supply. |
| BEV | Battery electric vehicle. |
| CAD | Computer-aided design. |
| DFM | Design for manufacturing. |

| | |
|---|---|
| DFMEA | Design failure mode and effect analysis. |
| DUT | Device under test. |
| EOL | End-of-line. |
| EMC | Electro-magnetic compatibility. |
| EMI | Electro-magnetic interference. |
| EMS | Engineering manufacturing service. |
| ESD | Electrostatic discharge. |
| EPO | Emergency power-off. |
| EU | European Union. |
| FuSa | Functional safety. |
| HDCIV | Higher dc input voltage. |
| HV | High voltage (as defined per IEC 60038). |
| HVa | High voltage (as defined per ECE R 100). |
| HW | Hardware. |
| IC | Integrated circuit. |
| ICS | Inductive charging system. |
| IEC | International Electrotechnical Commission. |
| LCR | inductance-capacitance-resistance. |
| LV | Low voltage (as defined per ECE R 100). |
| PES | Power electronics system. |
| PFC | Power-factor corrector. |
| PCB | Printed-circuit board. |
| PWB | Printed-wiring board. |
| PWM | Pulse-width modulation. |
| OC | Opto-coupler. |
| OEM | Original equipment manufacturer. |
| QRF | Quasi-resonant flyback. |
| R&D | Research and development. |
| ROI | Return of investment. |
| SN | Switching node. |
| SMPS | Switch-mode power supply. |
| SW | Software. |
| UL | Underwriters Laboratories. |

## VI. DECLARATION

Author declares no conflict of interests that could have influenced the work reported in this paper and does not endorse any manufacturer of electronic components, test and measurement equipment, or vendors of software. Also, no text was generated by using artificial intelligence (AI).

## ACKNOWLEDGMENT

Support from BRUSA management, especially Lukas Böhler, is appreciated. The author would like to thank Andreas Diefenthaler for his support with the thermal chamber setup and operation.

Some of the figures were made or edited by using *FidoCADJ* [95], *GNU Octave* [53], and *Libre Office Draw* [54]. The references were managed in Zotero [96].

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