Hardware-in-the-loop control of a modular induction motor drive in power electronics education

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Keywords

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Abstract

The development and the utilisation of a modular inverter for control of an induction or synchronous motor in a power electronics and electrical drives laboratory allows students to gain deep understanding. For easy deployment of own code and verification of analytical calculations a hardware-in-the-loop controller is used.

The laboratory hardware presented in [2] allows students to explore a variety of DC/DC-converter topologies. The most complex setup possible was an H-bridge designed for components with 200 V breakdown voltage at most. In order to extend the teaching concept presented in [2] to three-phase drives, a topology consisting of three inverter legs including an auxiliary voltage supply was developed extending the maximal component voltage to 600 V while retaining the modular structure.

In [2] the power semiconductors were controlled using an Arduino Nano, but its performance is by far insufficient for e.g. space vector modulation as commonly used in field-oriented control. Since the PLECS simulation software from Plexim GmbH is used in the power electronics and drive technology lectures, it was straightforward to use it in combination with hardware-in-the-loop (HIL) control. Plexim offers the RTBox CE as an inexpensive entry-level HIL-System. In the context of this publication, a RTBox CE is connected directly to the modular inverter driving a three-phase motor via an interface board. In order to apply a variable load the three-phase motor is connected in a motor test bench to a DC motor via a speed/torque measuring shaft. Actual values of rotor speed n and rotor angle γ are essential for field orientated control of the motor. Therefore the evaluation of the measuring shaft data is also performed by the RTBox.

The set-up, its possibilities and limitations are presented as examples within the scope of this work.

Introduction

University bachelor- and master-level power electronics and electrical drive education usually includes mandatory laboratory credits. Instead of using state of the art equipment from major companies it has been found that better outcome can be achieved using modular open frame components [1], [2], [4]. This allows for a deeper understanding of all involved hardware components including power electronic devices (MOSFET, IGBT), semiconductor material (Si, SiC, GaN), complementary gate drive, vector modulation and control, 3-phase AC machines (induction and synchronous motor), DC motor with external excitation, sensors (current, rotational speed, torque).

The most sophisticated part tends to be the shift from U/f-control to field orientated vector control of an induction motor. Therefor a hardware-in-the-loop (HIL) system using Plexim's PLECS as standalone simulator in conjunction with their entry-level HIL-system (RT Box CE) and PLECS-coder is used to control the power electronics and drives system in realtime [3]. Offline simulation of the entire system can be performed by students in advance to attending the laboratory session. This allows the students to implement and test control code prior to performing measurements which leads to a high level of understanding.

This paper is subdivided into three major parts. At first all hardware components used are described in detail. This includes both motors, the speed/torque measuring shaft, the modular inverter and the RTBox. The second part describes the implementation of the control with PLECS including data probing via the RTBox. Here, a few code examples are singled out for detailed discussion. Finally in the third part measurements both on system level and in detail are presented. Because of the open modular construction all voltages and currents can be easily accessed. In addition an exchange of e.g. Si $\leftrightarrow$ SiC freewheeling diode can be done on the fly, allowing to observe effects such as reverse recovery behaviour.

Hardware

Drive test stand

The drive test stand as depicted in Fig. 1 consists of a 3-phase AC-motor with slip rings in order to be operated either as induction motor or as synchronous motor, a rotational speed and torque sensor including an index impulse and a DC-Motor with separate excitation for recuperation.

Both motors can be operating using a single $0\dots350\,\text{V}$ laboratory power supply. In this case by using recuperation only system losses have to be covered. The easiest way to vary the braking torque of the AC-motor is to short circuit the DC-motor as depicted in Fig. 1 and to vary the excitation current $0 \leq I_E \leq I_{E_N}$. This will be done throughout this paper.

The nominal values of the machinery are:

1. 3-phase AC-motor Δ: $U_1 = 230\,\text{V}$, $I_1 = 1.44\,\text{A}$, $P_N = 270\,\text{W}$, $n_N = 1360(1500)\,\frac{1}{\text{min}}$, $I_E = 4\,\text{A}$
2. DC-motor: $U_{A_N} = 220\,\text{V}$, $I_{A_N} = 1.8\,\text{A}$, $P_N = 270\,\text{W}$, $n_N = 2000\,\frac{1}{\text{min}}$, $I_E = 250\,\text{mA}$
3. Torque/speed measuring shaft: $T_{\text{min/max}} = \pm5\,\text{Nm}$, sin / cos-output with $2\times360\,\frac{\text{pulses}}{\text{revolution}}$ with index impulse γ_0.

The torque/speed measuring shaft outputs the torque T as an analog voltage $U_T = \frac{1\,\text{V}}{\text{Nm}}\cdot T$, the rotation speed n as two logic level square waves $U_{\sin}$ and $U_{\cos}$ with $f_n = 6\,\frac{\text{min}}{\text{s}}\cdot n$ and the rotor angle reference γ_0 as open collector with $f_\gamma = \frac{n}{60\,\frac{\text{s}}{\text{min}}}$. The digital signals have 50% duty cycle and refer to $[n] = \frac{1}{\text{min}}$.

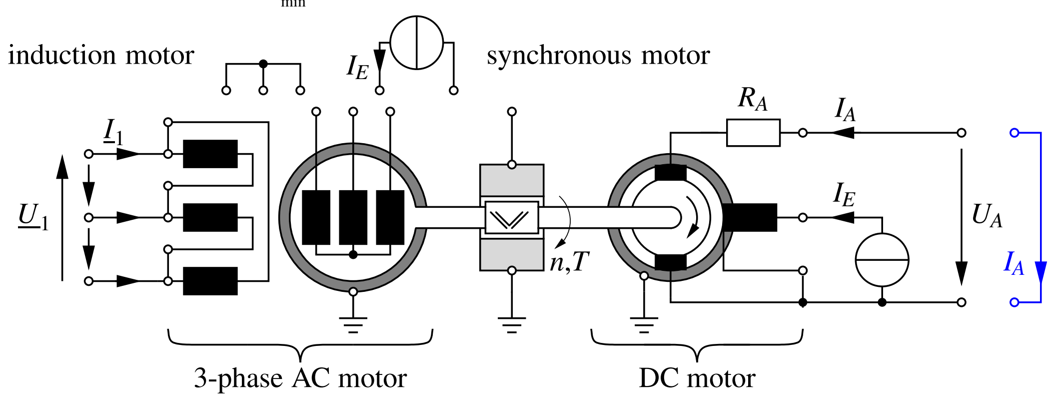

Fig. 1: Drive test stand, 3-phase AC motor, rotational speed and torque sensor, DC-Motor

Inverter

To allow students an easy recognition and understanding the modular power electronics concept presented in [2] is adopted. It consists of a half-bridge topology driven via a single driver (IR2131) incorporating a level-shift in conjunction with a bootstrap supply.

In order to maintain the modularity without compromising on issues as stray inductance an entire half-bridge including fault protection and phase current measurement is layouted on one PCB. This allows the use of 3 identical PCBs to ensemble the well known 3-phase voltage source inverter (VSI) topology. All clearances are chosen such to meet 600 V-requirements. All auxiliary voltages needed for drive and control of the inverter are generated via an additional PCB fed directly out of the DC-rail voltage.

Concluding the inverter hardware can be divided into the modular power electronics consisting of

- Backplane mainly populated with intermediate circuit capacitors and mounting all other PCBs
- 3× inverter leg including IGBTs and freewheeling diodes or MOSFETs and their gate drive, fault protection, fault status output and current measurement via a LEM current sensor
- Auxiliary power supply consisting of multiple DC/DC-converters generating +15 V and 5 V on DC-rail potential. In addition ±15 V isolated supply in order to decouple the HIL-System due to safety requirements. The operating voltage range is designed for $120\,\mathrm{V} \leq U_{\mathrm{DC}} \leq 350\,\mathrm{V}$. It is measured via a resistive voltage divider.

The complete inverter is depicted in Fig. 2 in combination with the RTBox and the interface board allowing for direct HIL-control of the inverter. Fig. 3 a) and c) shows schematic excerpts of one of the inverter legs and the auxiliary power supply respectively.

As a side effect the DC/DC-converter includes several converter topologies as there are flyback with a planar transformer, buck and buck-boost. They can be integrated into measurement and simulation and are therefore part of the possible educational outcome.

Hardware-in-the-loop (HIL)-System for rapid control prototyping (RTBox CE)

Plexim GmbH has designed a real-time simulator specially for power electronics applications. It works in combination with PLECS (Piecewise Linear Electrical Circuit Simulation) and their PLECS-coder which generates real-time C code from a circuit or block diagram created with PLECS Blockset.

While the entry-level RTBox CE is used throughout this work, the described hardware is upward compatible. A brief summary of the RTBox CE key performance figures is included in following table:

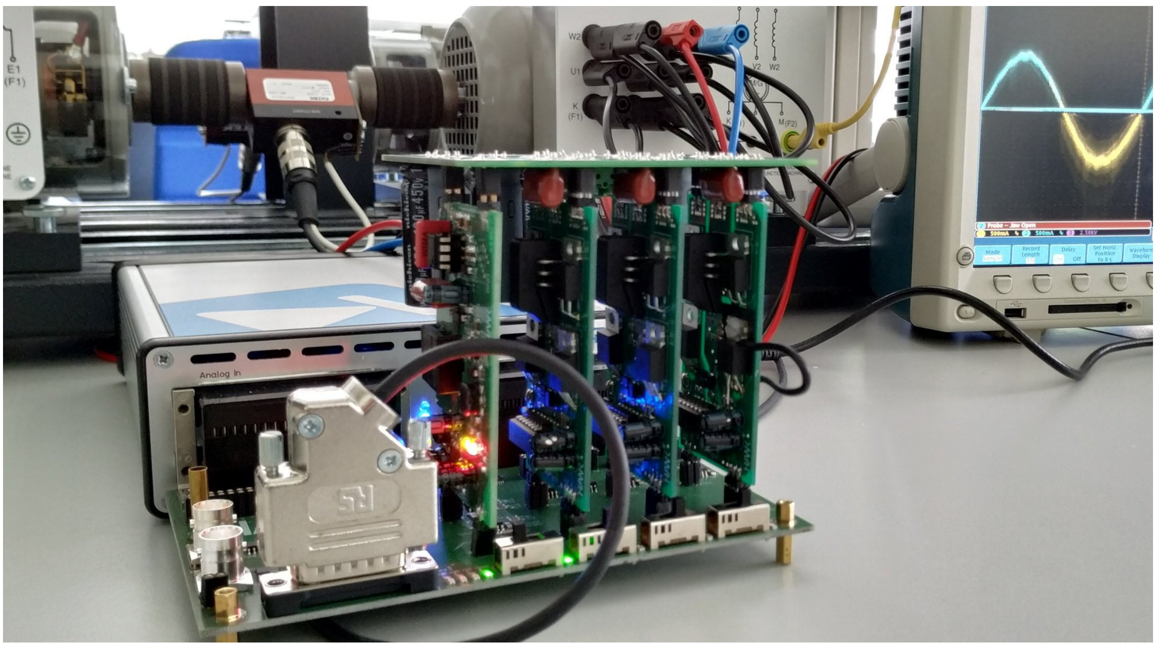

Fig. 2: HIL-control of the 3-phase AC motor, operating as induction motor

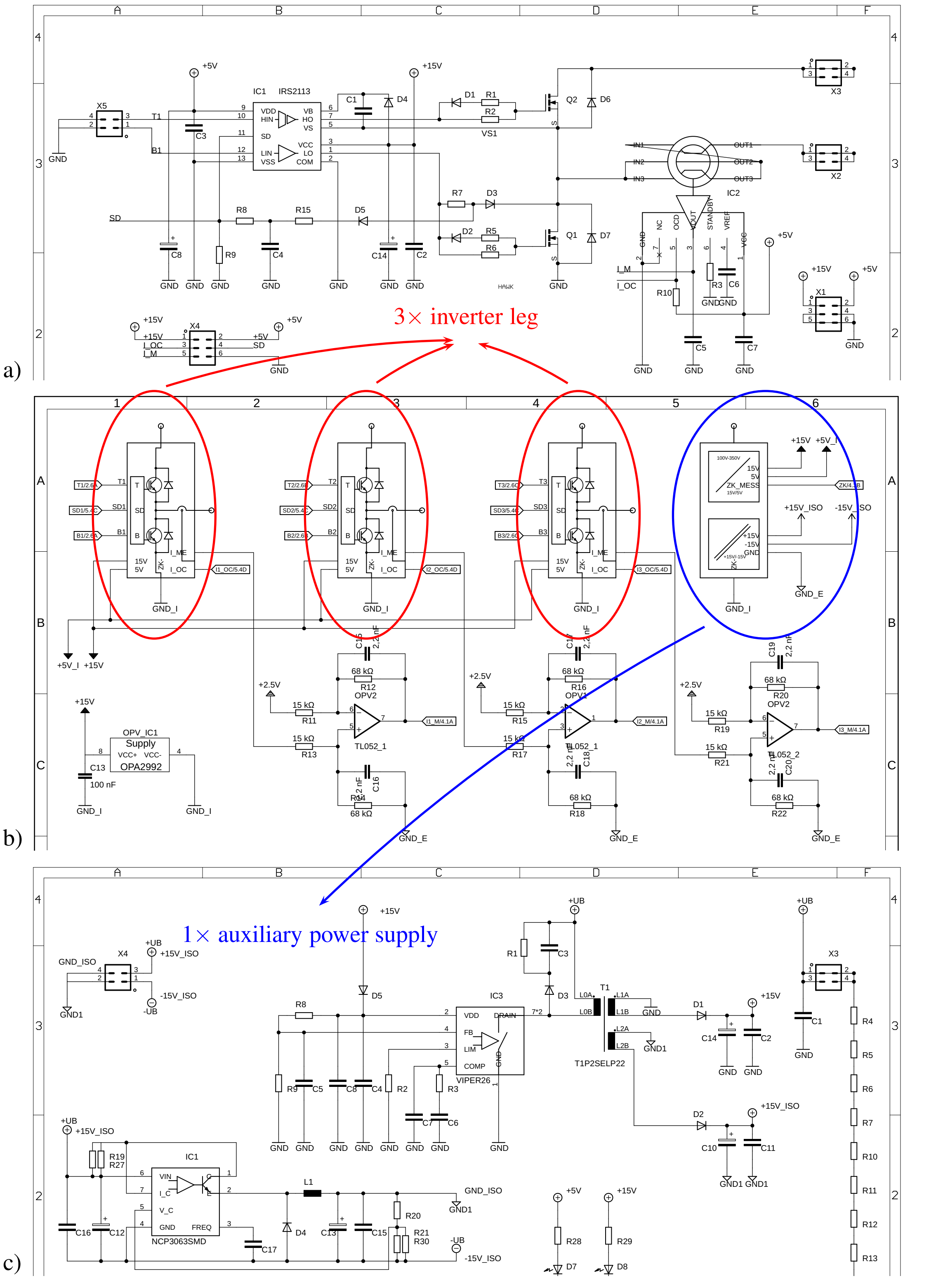

Fig. 3: Schematic excerpts, a) inverter leg, b) RTBox interface and c) auxiliary power supply

- Processor Xilinx Zynq Z-7030, CPU cores 2x ARM Cortex-A9, 1 GHz
- Analog inputs, 8 channels with 16 bit resolution, voltage ranges ± 5 V or ± 10 V, differential input, simultaneous sampling with 2 Msps at maximum
- Analog outputs, 16 channels with 16 bit resolution, voltage ranges single ended 5 V or 10 V, differential ± 10 V or ± 5 V, simultaneous update with 2 Msps at maximum
- Digital inputs, 32 channels, logic level 3.3 V (5 V tolerant)
- Digital outputs, 32 channels, logic level 3.3 V or 5 V
- Connectivity, gigabit Ethernet

Inside the RTBox, signal ground (gnd) and protective earth (PE) are not connected directly, in order to avoid ground loops that might otherwise. The safety and grounding concept of the described setup is included in Fig. 4 giving an isolation and potential overview.

The performance of the RTBox CE is sufficient to run the code described in the software section of this paper with a discretisation step size as small as $T_S = 5\,\mu$s which is sufficient. An even smaller step size may be chosen in case of less extensive code.

Interface board, RTBox to inverter

The interconnection between RTBox and inverter is attempted to be both reliable and structured in order to allow students to work safely and with reproducible outcome. Plexim offers similar interfaces for Texas Instruments LaunchPad evaluation boards. This concept has been adopted.

The main difficulty was to ensure safety by design. In case of any inverter malfunction it has to be ensured, that the maximum voltage levels between the RTBox inputs and outputs, all connected instruments such as oscilloscope and/or signal generator does not exceed $\pm 24\,$V in order to prevent personal and equipment damage.

This goal was met by isolating the inverter ground (ignd) from the RTBox ground (gnd). Both grounds are connected at one point only via an inductor which avoids any DC voltage but decouples both grounds at higher frequency e.g. during transients. As stated above RTBox ground and protective earth (PE) are not connected inside the RTBox. This concept fails in case of connected measurement instruments with inputs or outputs referring to PE, which usually is the case. Therefor ground (gnd) and protective earth (PE) are connected on the interface board.

Digital signals are passed inbetween RTBox and inverter using magnetically isolated digital isolation (iCoupler ADuM225N, Analog Devices). This includes 3×2 gate drive signals and 2 overcurrent fault signals. All analog signals including $3\times$ phase current measurements and $1\times$ DC-rail voltage measurement use discrete differential amplifiers. An overview mainly showing the chosen isolation and potential scheme is included in Fig. 4. A foto of all PCBs is depicted in Fig. 5.

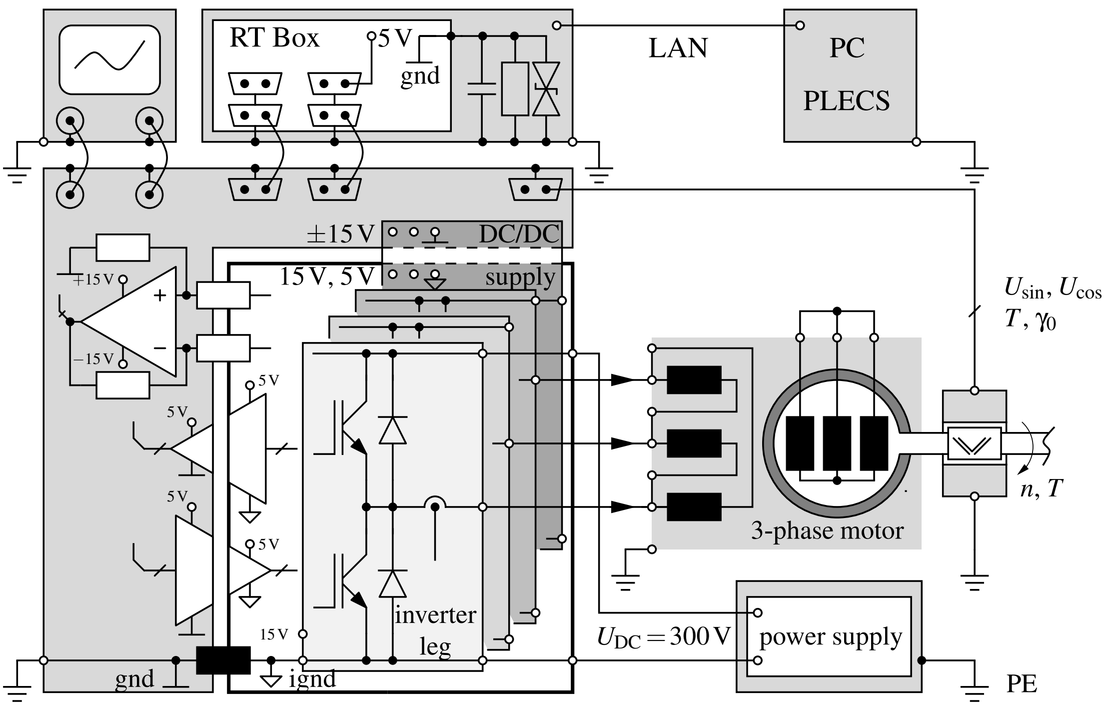

Fig. 4: Isolation and potential overview including RTBox with inverter, PC running PLECS, induction motor, torque/speed measuring shaft, laboratory equipment (power supply, oscilloscope, ...)

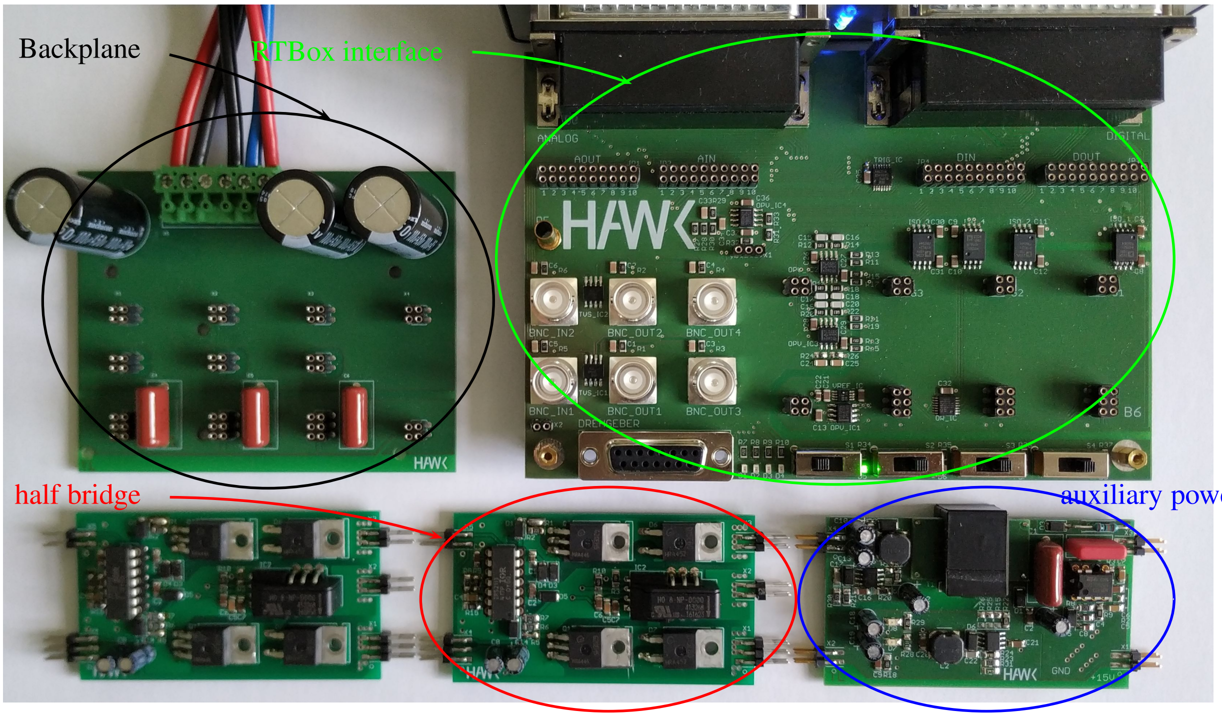

Fig. 5: Inverter, interface and backplane PCBs in top view

Two analog inputs and four analog outputs of the RTBox are accessible via PE referenced BNC connectors. Four digital inputs and outputs are connected to hardware switches and LEDs respectively. The RTBox uses four 37 pin D-Sub connectors for analog/digital in-/ and output.

In addition the digital and analog torque/speed measuring shaft outputs are inferfaces using a 15 pin D-Sub connector and processed via Schmitt trigger and the an active lowpass filter respectively.

Software

The control software is generated automatically using PLECS and PLECS-coder. Usually a board support package has to be developed in order to adapt to external microcontroller or DSP based control hardware. Obviously this is included for Plexim's own RTBoxes and for some DSPs. In the scope of this paper only the RTBox will be used.

The software development is done in 4 steps.

1. PLECS model of the drive test stand as depicted in Fig. 1. As this model can be reused, this has only to be done once.
2. PLECS model of the power electronics. This can also be reused by the students. At this point a clear interface naming and structure is essential, because in HIL simulation this will be the interface between RTBox and power electronics and electrical drives.
3. PLECS model for offline control of above components. This is the component developed by the students themselves. These 3 software components allow for offline simulation.
4. In order to deploy the offline control software for realtime control the PLECS-coder builds, downloads and starts the entire model for the chosen hardware.

The development of a a PLECS model including step 1 to 4 is shown in two examples.

Torque/speed measuring shaft

During offline simulation torque, speed and rotor angle can be probed using the AC motor, the DC motor or separate meters provided in PLECSs mechanical domain. The drive test stand for offline simulation including the inverter is depicted in Fig. 6 (top, blue rectangle).

In order to ensure compatibility to the real torque/speed measuring shaft the output signals as described in the hardware section have to be generated. PLECS allows for the implementation of C-code directly,

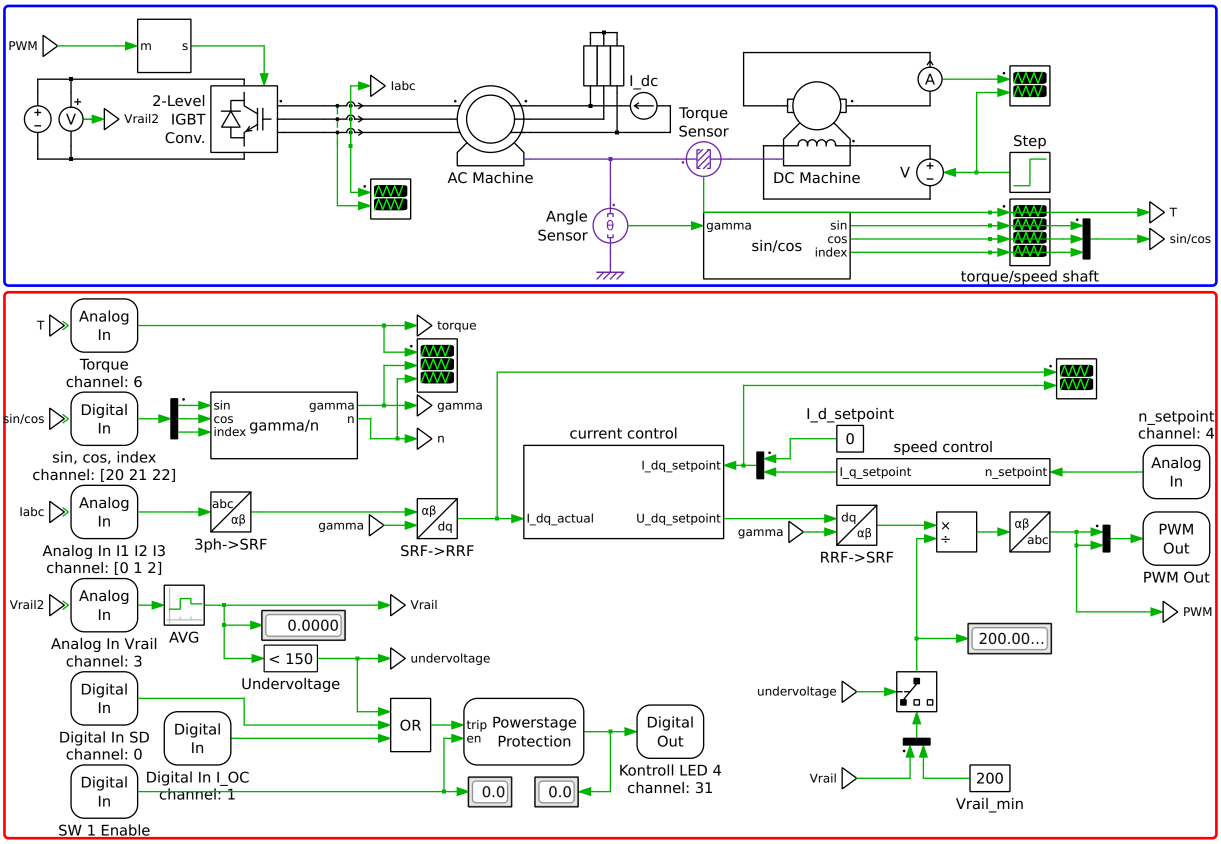

Fig. 6: PLECS, realtime/offline simulation including RTBox interfaces for drive output and measurement input including the torque/speed measuring shaft

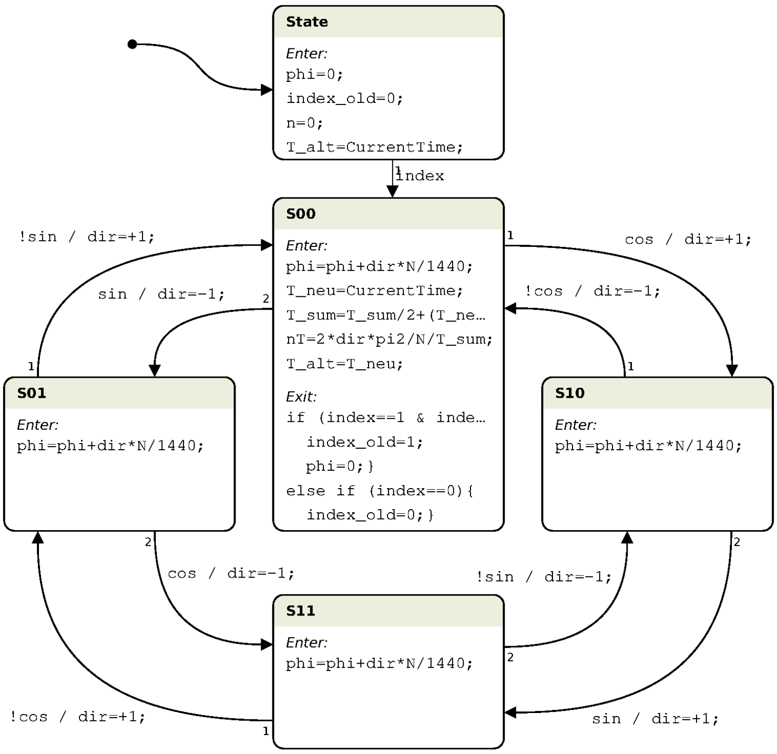

Fig. 7: PLECS, state-machine generating realtime outputs for rotor angle γ and speed n

defining input signals with arbitrary code of any complexity calculating the outputs signals. This has been used to generate the outputs $U_{\sin}$, $U_{\cos}$ and γ_0 using $\gamma(t)$. The code is added into a user defined subsystem called *sin/cos*. This subsystem is also included into the user library.

During realtime simulation the torque/speed measuring shaft outputs are connected to the RTBox digital and analog inputs via the RTBox interface. Instead of using C-code a state-machine is used to calculate the rotor angle γ and the rotor speed n. The code of the single states of the state-machine also uses C-code. Fig. 7 shows the states including their enty- and exit-code. State-machines have been proven to be more transparent and easier to implement. The described state-machine is included into a user defined subsystem called *gamma/n*. It has also been added to the user library.

The PLECS model depicted in Fig. 6 allowes for developing and testing. For HIL simulation using the real drive test stand and the RTBox including interface and inverter, only the code depicted in Fig. 6 (bottom, red rectangle) is necessary. Fig. 8 shows a screenshot of PLECS running in external mode after building and deploying the model into the RTBox. The probe data is captured in the RTBox and transferred to the connected PC via LAN. On the right hand side T, γ and n are captured showing a load step $T = 0 \rightarrow 1.5\,\mathrm{Nm}$. The trigger source and level can be set using the external mode of PLECS-coder.

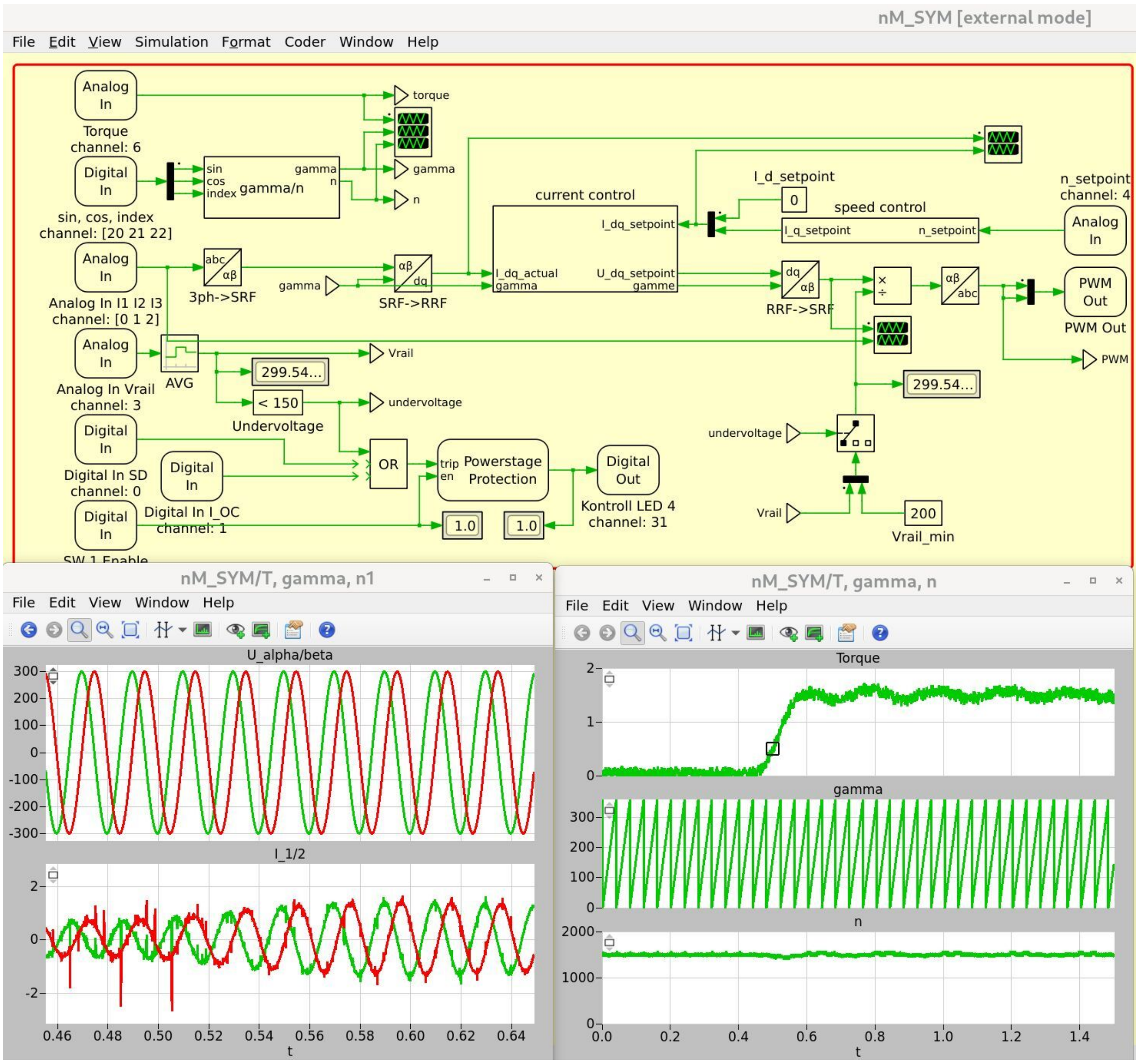

Fig. 8: PLECS running in external mode, PC connected to RTBox triggering and updating scope signals

Inverter drive

A second example is already included in Fig. 6. The AC motor, operated as synchronous motor, can be controlled via an analog speed setpoint which is fed into the RTBox interface e.g. using a signal generator. The speed control and the current control is modelled using continuous state block elements in equally named subsystems. In this case simple PI-controllers are used. The current control inputs the actual and the setpoint stator current as space-vector and outputs the desired voltage space-vector which has to be transformed back into stator-reference-frame. After Clarke transformation the inverter drive signals are generated using a pulse width modulation. Sadly the RTBox board-support-package does not provide a space-vector-modulation. Therefore only a symmetrical PWM has to be used via the *PWM Out*-block. An advantage of these blocks is their included fault protection using the *Powerstage Protection*-block ensuring safe shutdown in case of undervoltage or overcurrent.

The system response can be changed and observed easily. In this case the above mentioned load step $T = 0 \rightarrow 1.5\,\mathrm{Nm}$ is imposed using the DC motor as eddy-current brake while maintaining the drive speed of $n = 1500\,\frac{1}{\mathrm{min}}$. Again PLECS-coder in external mode is used to capture and to display realtime data. On the left hand side of Fig. 6 two line currents as measured in an inverter leg, transferred via a differential amplifier on the RTBox interface and sampled by the RTBox are displayed along with the stator voltage setpoint in stator-reference-frame $\vec{U}_1 = U_\alpha + \mathrm{j} \cdot U_\beta$. Because all three line currents are sampled simultaneously (although two would be sufficient) the current can easily be transformed into a line current space-vecor $\vec{I}_1$ using either stator- or rotor-reference-frame. The later is needed for field orientated control.

This code was used to operate the AC-motor as synchronous motor performing the following measurement examples.

Measurements

Above PLECS model operating as HIL controller is capable of displaying measured data, variables etc. using the PLECS-scope via the PLECS-coder in external mode as depicted in Fig. 8. This option is limited to the sampling frequency which in turn is determined by the model complexity. In this case $f_S = 200\,\mathrm{kHz}$ ($T_S = 5\,\mu\mathrm{s}$) is chosen.

In order to observe fast switching events and to investigate e.g. the effect of SiC or GaN diodes the use of an oscilloscope is inevitable. Because of the open structure of the modular inverter it is possible to measure any signal of interest. This is shown in Fig. 9 comparing the effect of a line current commutating from the top diode into the bottom IGBT. The devices used are IBBTs IGP20N65H5, EmCon diodes IDP23E60 and the SiC Schottky diode IDH03G65C5 for comparison all from Infineon. The reduceced current peak due to the lack of reverse recovery charge Q_{rr} is eminent. This in turn reduces the turn on losses of the IGBT.

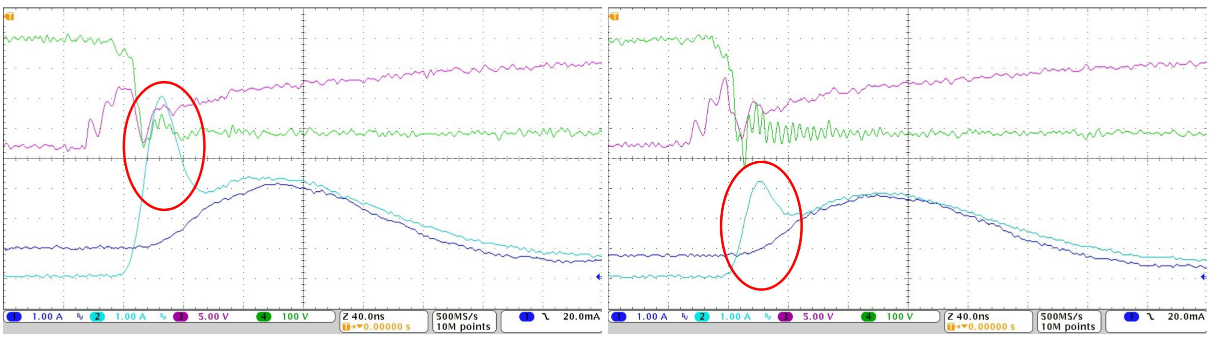

Fig. 9: Si versus SiC freewheeling diode (1) I_{line}, (2) I_{IGBT}, (3) U_{GE}, (4) U_{CE}

Of course line current and line voltage measurements as depiceted in Fig. 10 are also possible. They allow students to verify offline simulation results and deepen their understanding. Because PLECS intends for system level simulations the effect of fast transients is observed best by performing measurements.

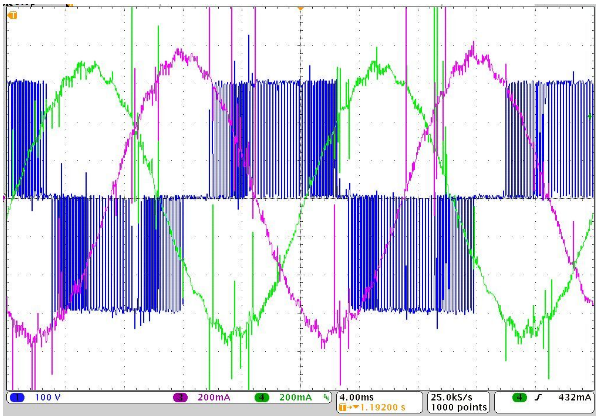

Fig. 10: Line voltage (1) U_{12} and line currents (3) I_{L1}, (4) I_{L2}

Conclusion

Modern simulation tools such as PLECS can automatically generate efficient code for either HIL-systems, microcontrollers or DSPs. Usually HIL-systems are used for real time simulation of e.g. the drive train in order to speed up control code development spire to finalisation of the drive train. For education purpose it is desirable to turn this around.

The graphical modeling of the control code and its deployment into a HIL-system allows students to concentrate on the underlying control principles such as calculations and transformations using space-vectors in different reference frames. The performance of the Plexims RTBox CE is sufficient for driving the described voltage source inverter including measuring the stator currents, the rail voltage and operating the torque/speed measuring shaft at a switching frequency of up to $f_S = 10\,\mathrm{kHz}$.

Despite the lack of e.g. space-vector-modulation in the board support package the software has proven to be easy to use and the education outcome is superior to only performing measurements with commercial converters. Later do not allow for the deployment of own code and therefore the system has to be regarded as a black box which only accepts a set of parameters.

An additional advantage is the ability to perform both measurements on system and on component level. This allows for the investigation and the comparison of new components such as SiC or GaN devices.

The system described in this paper has already been used in a drive-systems master course generating a very promising outcome. This strategy will be expanded to more motor types and different control strategies in the near future.

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