# Power electronics and drives laboratory learning environment for electric vehicles

Peter J. van Duijsen
*THUAS*
*www.caspoc.com*
Delft, The Netherlands
p.vanduijsen@caspoc.com

Diëgo C. Zuidervliet
*THUAS*
*dc-lab.org*
Delft, The Netherlands
d.c.zuidervliet@hhs.nl

***Abstract*—The popularity of electric vehicles as a study object among students in the engineering sector is rising. Although there is a wide variety of educational textbooks and training material for theory, the choice of laboratory set-ups for motor control is limited to large and costly technical trainers on one side and vendor specific microcontroller demonstration kits on the other side. In this paper the requirements and implementation of a laboratory set-up is discussed which can be used to teach the application of motor drives including permanent magnet dc motors, brushless dc motors, stepper motors and permanent magnet synchronous motors. The laboratory set-up can be combined with either an analog control for cascaded current, speed and position control, or a digital control can be added for a sensorless brushless control and the field oriented control of the permanent magnet motor. The digital control is ranging from a cost-effective Arduino-nano, STM-Nucleo to the Field Oriented Control enhanced C2000 platform, including the Instaspin-FAST(sensorless) microcontrollers. The student learning objectives include the details for the inverter topology, like gate driver and shoot through protection and blanking time compensation as well as setting up current-torque control on the dc and permanent magnet synchronous machines and finally the implementation of a field oriented controller. Various modulation schemes can be implemented as well as the methods for sampling motor terminal currents and voltages. An extensive set of online-simulations is guiding and preparing the student for each laboratory exercise.**

***Index Terms*—power electronics, drives laboratory, learning environment, electric vehicles, simulation, pmsm, ipm, brushless, embedded control**

## I. Introduction

TEaching motor drives is based on many disciplines. Traditionally motor drives was mainly considering the operation of the most popular electrical machines, like dc motors, induction motors and synchronous generators [2], [3], [5]. In [4] the classical text on electric machines is more oriented towards electrical drives. In modern drive applications the role of power electronics and the role of control are coming together as equally important parts. Therefore all three parts have to be part of the curriculum of the modern drive engineer. In this paper examples are discussed that can be part of an electric drive curriculum. The subject is very wide and there are many different types of electric machines, drives and control principles. There is also a large variation in drives ranging from very low power levels for dc motors to very high power levels for large industrial drives.

Especially in education, laboratory exercises are important for the understanding, but the laboratory exercises are very limited regarding the power range of the various electric machines and drives. However simulation and animation [8] provides an extra addition to the laboratory exercises.

There are mainly three subjects in teaching electrical drives that require special attention, when the aim is to teach the complete working of electrical drives. In section II some examples of typical basics of electrical machines are discussed. It all starts with the most easy to understand and well known brushed DC motor and continues up to induction machines and interior permanent magnet synchronous machines. The power electronics to drive the electrical machine is discussed in section III. Control of the motor using an embedded control completes the electrical drive and is discussed in section IV.

The application of a Brushless drive using Hall sensors and a very simple control is discussed in section V. Students can build this setup and do measurements on the drive and since the control is straightforward and everything works with low voltage and current levels, it is also safe for experimenting by the students.

The application of traction motors and electric vehicles would be the best, if it could be carried out full scale. However not every laboratory does provide a setup where a motor$> 100kW$ can be tested, or even let a student play with it. Here simulation, see figure 1, is required to teach the basics of field oriented control and a small scale model with embedded control already demonstrates all necessary steps required to drive an interior permanent magnet synchronous machine. In section VI the simulation of the field oriented control of an interior permanent magnet synchronous machine is shown and secondly it is shown how the embedded control can used to control a small scale motor laboratory setup.

## II. Electric machines

DC motor torque control is usually the first encounter of electrotechnical students with electrical machines. Nothing changed in the last hundred-fifty years [1] except that the DC

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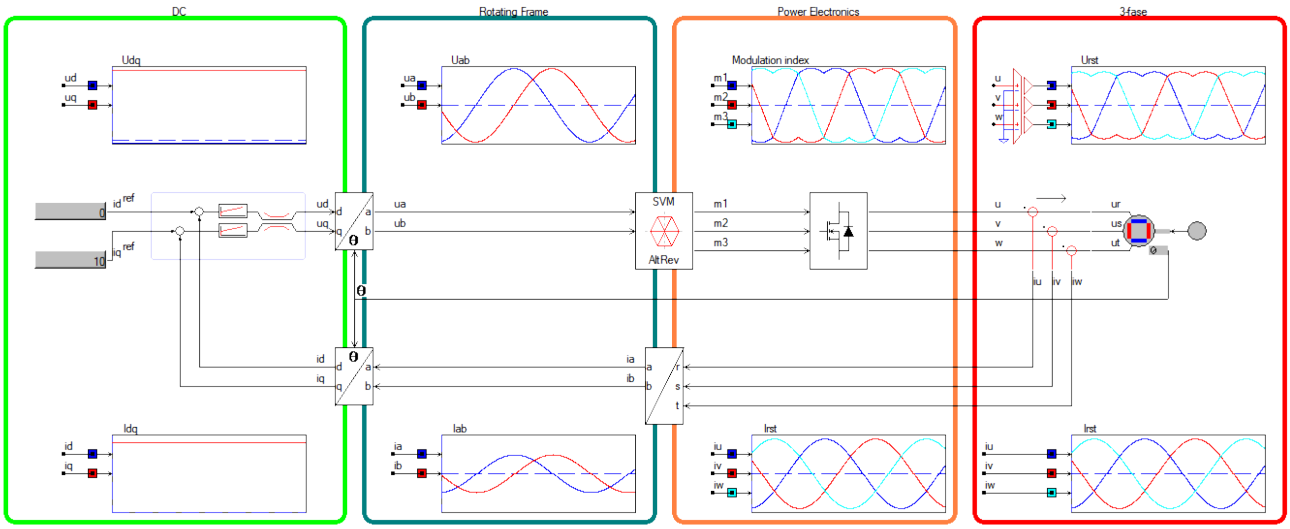


Fig. 1. Basics of Field Oriented Control in three phase motors.

machine lost its importance in heavy industry, however still around us for small applications. Nonetheless, the operation of the DC motor still forms the basic understanding for field oriented control, as for students they can see that torque is generated as the product of flux and current.

$$T = I \times \Psi \tag{1}$$

$$U_{EMF} = \omega \times \Psi \tag{2}$$

In figure 2 it is shown that flux and current are perpendicular and therefore the dc motor creates torque.

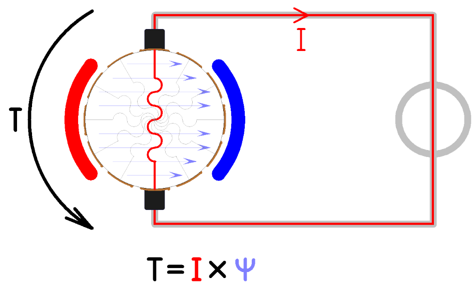


Fig. 2. Basics of torque generation in a DC motor.

Secondly the relation between motor back emf $U_{EMF}$ and rotor angular speed $\omega$ is important to understand for the students. Only then they can understand the drive concept and the relations between the voltage rating, current rating, maximum power and maximum speed. This concept then has to be translated towards three phase motors and this is where field orientation comes into play.

One can start with presenting all Park and Clarke transformations [4], but visualizing the waveforms makes it easier for students to understand. In figure 1 the transformations are shown by means of three phase voltage and currents, their $3 \rightarrow 2$ transformed values and finally their $d-q$ values in the synchronous reference frame. Here the scopes in the upper row show the voltages, while the scopes in the lower row show the currents. On the left side in figure 1 is the synchronous reference frame, where the control variables are in he $d-q$ steady state format. PI controllers regulate the voltage, based on the error signal between reference and measured currents. Although the simulation contains a minimum of components, the basics of field oriented control can be explored, including the effect of control and motor parameters on the dynamic behavior.

## III. Power Electronics

For running three phase motors in a laboratory setup, a power electronics inverter is required. Although an industrial drive could be used, the educational aspect such a measuring and validating voltages and currents in the drive system is sometimes complicated. For this purpose a universal four leg, [U4L] [11] was created. Since this inverter is versatile and can be used for many different applications, it not only allows the students to measure all voltages and currents, but also shows the basic of power electronic components, such as Mosfets, gate drivers and current sense circuitry required to build a functioning inverter. Since students can measure all signals starting from the modulation signals at the input of the inverter up to the gating signals of the Mosfets, they are, for example, able to see where blanking time is introduced and how the bootstrap circuitry at the gate driver is configured.

The power electronics inverter that is used to control a brushless permanent magnet motor is shown in figure 6. Current through the motor winding is measured inside the inverter using a series resistor and a differential amplifier with high bandwidth. A typical output of such a differential amplifier is shown in figure 7. The current is scaled and centered around 2.5 volt for embedded microcontrollers working at 5 volt like

Arduino [14] and a lower voltage level for 3.3 volt supplied microcontrollers. A dual motor setup like in figure 6 can be used to control speed with one motor and torque with the other motor. If both power electronic inverters are fed from the same supply, the net energy is close to the losses the entire set produces.

## IV. Embedded Control

For brushed DC drives a setup can include an analog control build around operational amplifiers configure as PI controllers, see [10]. Also for brushed DC motors operating in a single quadrant, e.g. motor operation only, the current control can be build around a general current mode controlled switched mode power supply[SMPS] IC. In [9] a brushed universal motor in a vacuum cleaner is controlled using a general purpose SMPS. When it comes to Brushless three phase motors, a digital control using NAND gates is possible to build [7], but already adding pulse width modulation using an external duty cycle controlled signal, makes the overall control structure complex considering the amount of wires connecting all logical NAND gates. A simple Arduino [14] can be programmed easily to control a brushless motor. However for sinusoidal controlled currents, a more sophisticated control algorithm with a higher bandwidth is required. The C2000 microcontroller [15] is used in our laboratory setup because it includes a sensorless observer[FAST] for Flux, rotor Angle, motor Speed and generated Torque.

## V. Application Brushless motor drive

The brushless motor is suitable for a first introduction in three-phase motor control. The simplicity of the geometrical structure of the motor as well as the logical control, where each time the next stator pole is excited in order to attract the rotor magnet pole is readily understandable by students. The students can follow each signal in the brushless drive, form the Hall sensor output up the the motor terminal voltage a winding current. In figure 3 the cross-section of a typical 2 pole brushless motor is shown.

In figure 4 the Hall sensor signals, voltages and currents of a typical brushless motor as shown in figure 3 is shown. The students can choose the number of poles and if the Hall sensors are configured in $120\,\mathrm{deg}$ or $180\,\mathrm{deg}$ control sequence. By rotating the rotor via a slider, the students see the rotor with magnets rotating and the indicator(vertical black line) in figure 4 shows the position along the circumferential airgap with the corresponding voltage, currents and Hall signals.

From top to bottom in figure 3 the back emf phase voltages of the motor, the terminal line-line voltages and line-line back emf voltages are shown. The currents are shown like blocks, since using PWM modulation the current does not have to be a constant value. The Hall signals are shown with the corresponding colors as the Hall sensors in the cross section of the motor in figure 3. Tasks for students include figuring out the connections, that have to be made to drive the motor. Since the U4L has current limiting protection, students can play around with various configurations. The students can be

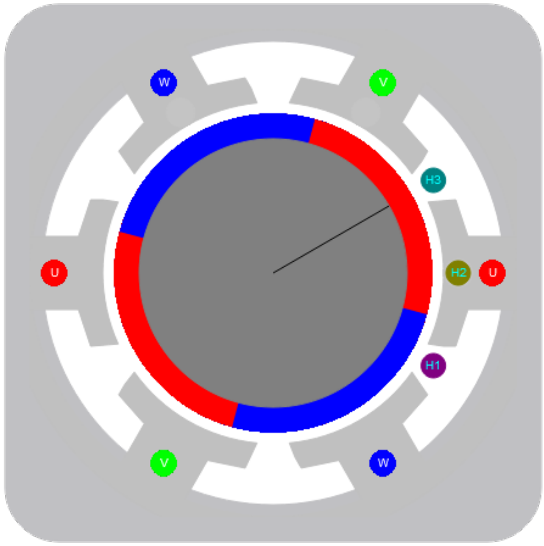


Fig. 3. Brushless drive motor cross section.

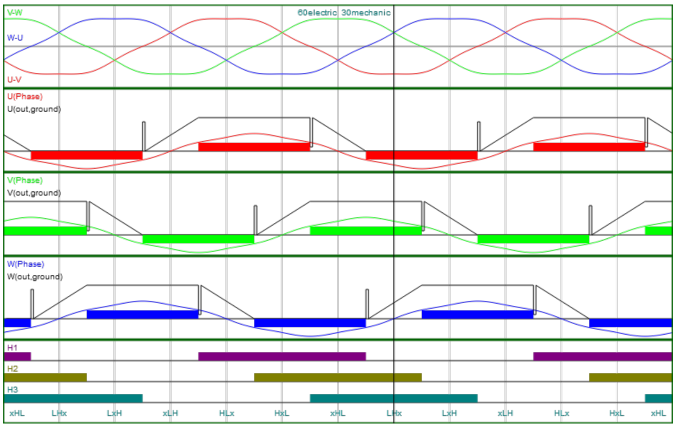


Fig. 4. Brushless drive motor control signals.

assigned to develop a control algorithm for the Arduino [14], or they can be assigned to follow all signals and to come up with the idea how to reverse the speed of the motor with minimum modification. Before the students are allowed to work on the physical setup they first have to understand the operation and the way the Hall signals are translated into gating signals for the Mosfets. Also they have to understand what motor current to expect and what will be the final speed of the motor. To prepare the students, a simulation as shown in figure 5 is given to the students where they have to study all the voltage and current waveforms in conjunction with the Hall signals. During the simulation in [12] the animation is enabled and the students will see the rotor angular position, and which winding is energized. The Freeze and Go-Back feature [8] allows them to go back in time and to observe each commutation, by sliding a cursor back and forth and see the momentary voltage, current and signal level as well as the

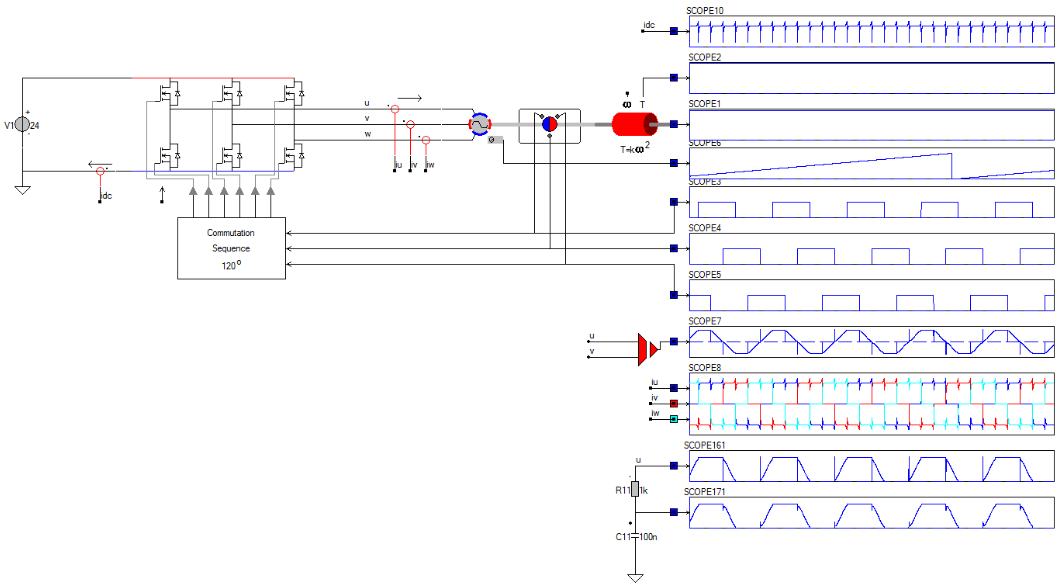


Fig. 5. Brushless drive simulation in Caspoc [12].

angular rotor position.

The simulation in figure 5 shows the ideal voltage and current waveforms. In reality, the measured voltage is used in the next assignment, where detecting the zero-crossing of the voltage is used for sensorless operation. Therefore the measured voltage is filtered by an RC filter and in the simulation the students are prepared to investigate the bandwidth and phase shift of such a filter. The last two scopes in figure 5 show the measured and filtered phase-ground voltage which is measured between the output of the inverter and the ground terminal of the inverter. The filtering of the effects cause by the commutation becomes visible. Also the commutation effect on the current as visible in scope8 in figure 5 has to be understood by the students. The students have to explain what is happening during commutation and where the notches in the voltage waveform as shown in scope7 in figure 5 are coming from. By using the Freeze and Go Back feature and the animation in Caspoc [12] the students can verify the origin and by changing the motor parameters in the simulation they are able to explain the origin of these notches.

In figure 7 a typical effect is visible and the student have to explain what is measured and why the measured current is not as what would be expected as explained during the theoretical part in figure 4 and in figure 5. They should notice that the motor terminal voltage is not constant and that this could be the reason way the current is not going to its maximum value. It is left to the students to figure out that the back emf of this motor is not rectangular as in the simulation, but sinusoidal.

## VI. Application Traction Motor Drive

The application of an evehicle traction drive requires an industry standard solution to be used as laboratory setup. The main educational goals are on the design of the embedded control. The learning objective can be either to understand the principle of field oriented control, or to design the cascaded speed/current controllers for a typical traction drive. Using the simulation like in figure 8 the complete drive system is

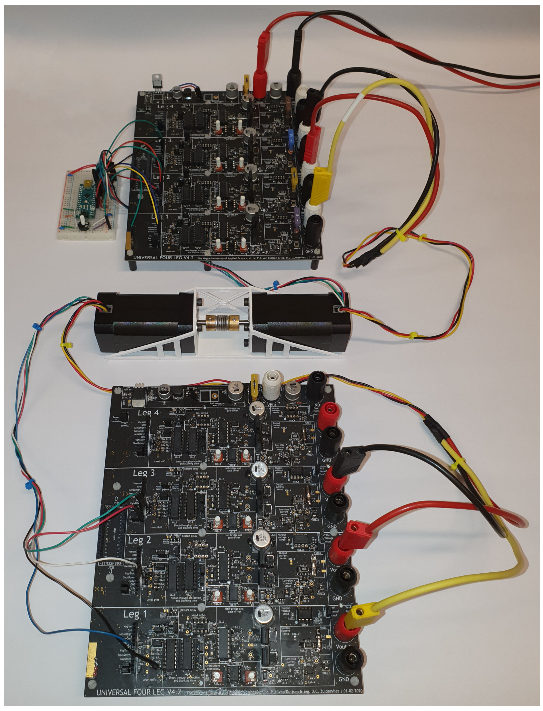

Fig. 6. Dual drive, top inverter plus right motor control speed, bottom inverter and left motor control torque.

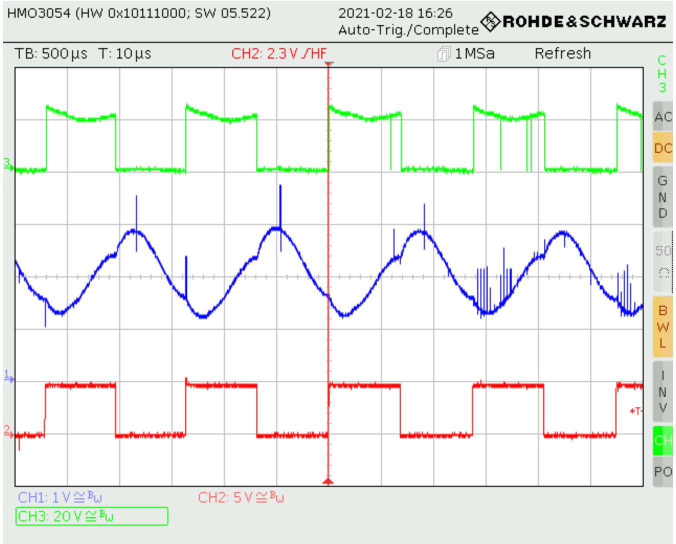


Fig. 7. Brushless drive motor control signals, from top to bottom; CH3(green): Inverter terminal voltage, CH1(blue): current phase A, CH2(red): Hall Sensor phase A

verified and all control parameters are optimized. The aim of this simulation is to verify that the parameters for the PI controllers are giving the expected dynamic behavior. The sampling interval as given by the timing of the embedded control is included in this simulation, as well as the switching of the mosfets in the inverter with Space Vector Modulation [SVM] [4]. The effects of the modulation are the harmonics on the voltage waveform and the therewith associated harmonics in the current waveform. The torque as a result of this modulation drives the mechanical quadratic load that mimics an electric vehicle. The model can be extended using mechanical models for the drive shaft, coupling and gearboxes and vehicle-dynamics models as well as a more detailed machine model with saturation and thermal effects, but here the emphasis is on the parameters of the current controllers in the d-q synchronous rotating reference frame.

### A. Simulation of the complete drive

The next step is to implement the parameters from the simulation in Caspoc [12] in an embedded control. For this a setup includes a microcontroller, inverter and Interior Permanent Magnet [IPM] motor [4]. To shorten development time and to ensure that the to be implemented control code is correct, use is made of the C code generator and compiler in Embed [13]. This evolves in three steps. First a system simulation is carried out to prove hat the implemented control structure and its parameters are correct. Secondly the C code of the control structure is generated, compiled and uploaded in the microcontroller. In the third stage, the microcontroller with embedded control is started and the measured signals from the microcontroller are returned to the user interface during running the motor. In this stage the user can change the input settings for the control, like reference angular speed, currents and even the parameters of the PI controllers.

### B. Simulation of the embedded control

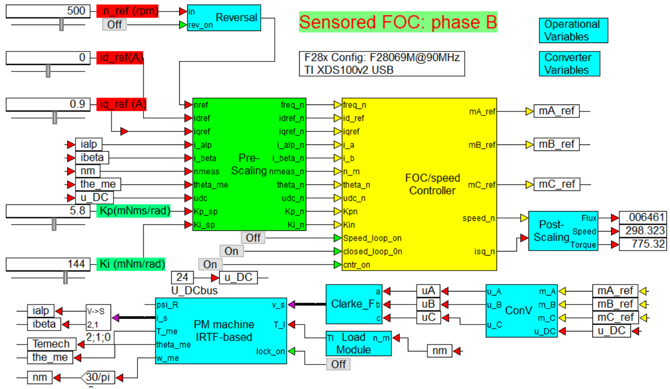


Fig. 9. Simulation of PMSM motor drive to test the implemented control.

In figure 9 the system simulation in Embed is carried out. The parameters $Kp$ and $Ki = Kp/\tau$ from the PI controllers from the Caspoc simulation in figure 8 are taken as well as the sampling time which is entered in the boxes [Operational Variables] and [Converter Variables] in the simulation in Embed in figure 9. The Yellow block entitled [FOC/Speed Controller] contains the complete control structure that is going to be used in the microcontroller. The rest of the block diagram is a simplified model for the IPM motor, sensors and inverter. The simulation should verify that the control structure in the block [FOC/Speed Controller] is correct. Once this simulation proves the same results as those from the Caspoc simulation in figure 8, one can proceed to the next stage where the control structure is generated and implemented into the microcontroller.

### C. Compilation of embedded control

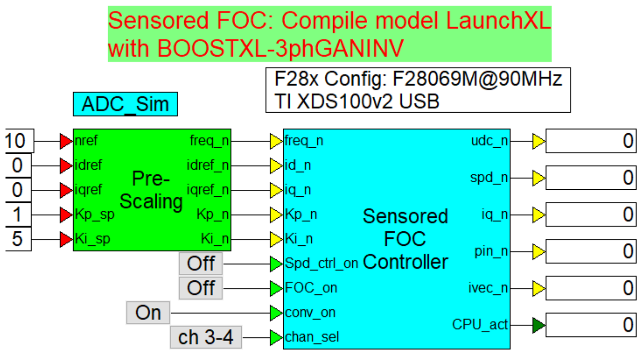


Fig. 10. Compilation of control into C code to be uploaded into the microcontroller.

For each stage in the process of implementing the embedded control as special model is given to the students, so they can directly apply it. during stage C The C-code is generated, compiled and uploaded into the microcontroller using the model in figure 10. Only the contents of the block [Sensored FOC Controller] are uploaded into the micro controller.

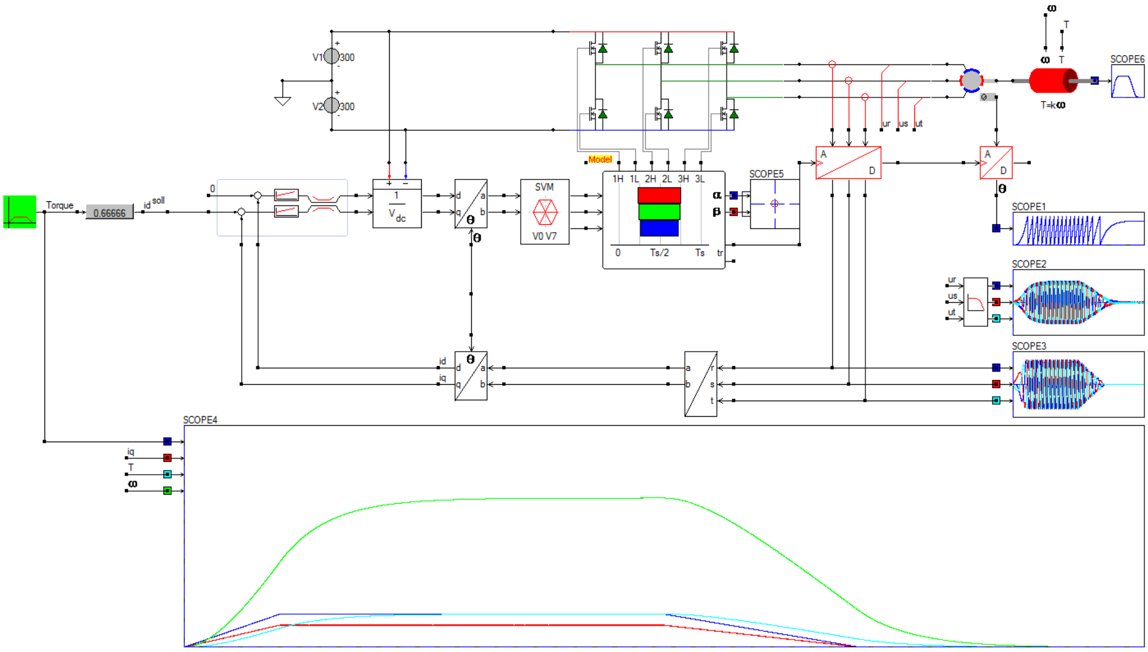


Fig. 8. Simulation in Caspoc [12] of a Field Oriented Control of an IPM motor.

### *D. Running the motor using the embedded control*

Upon completion of stage C the motor is running once activated from the user interface in Embed. The user interface in Embed,see figure 11, is used to set control parameters and to observe the machine speed and currents depending on the given inputs settings for the reference speed.

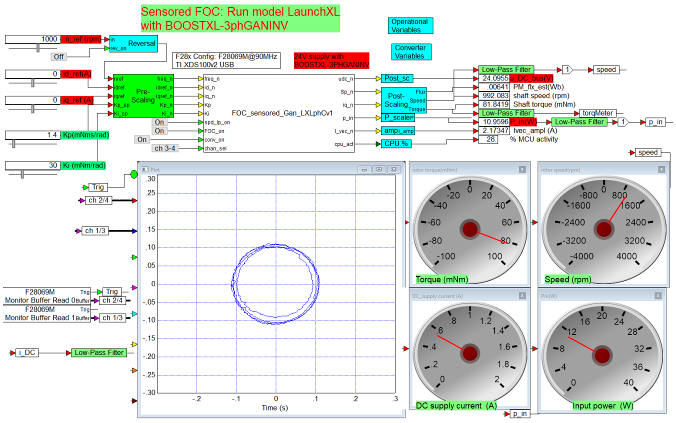


Fig. 11. Running the microcontroller plus inverter plus motor via user interface to control the settings.

## VII. Conclusions

Traditional motor control evolved from classical theory on electric machines to practical implementation of a complete drive in a laboratory setup. Students are prepared via simulations and animations and gradually move from the basics of brushed dc motors, via brushless dc towards synchronous permanent magnet motor drives with embedded control. Dedicated hardware like the U4L enables the measurements of all voltages and currents in the drive and gives insight in the overall operation of a drive. The use of simulation and automated code generation allows the students to focus on the drive dynamics and parameters.

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