

A supplementary tool to the standard teaching method of induction motor drive control

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Abstract—This paper demonstrates a modern approach to teaching motor drive control, which can be used as additional tool to the standard education methods or even completely self contained. Emulation-based virtual laboratory is proposed for control engineering education purpose. By using the example of induction machine digital control, there is shown that emulation experiments can give students an industrially relevant educational experience. Both digital controller design steps and suitable emulated power stages, together with experiment results are presented in detail.

Keywords- *Controller, Motor drive, Hardware-in-the-Loop, Education*

I. INTRODUCTION

Education in applied fields, such as control engineering, can take many forms ranging from highly theoretical to deeply vocational. Typically, theoretical books cover the “what” rather than the “how.” Thus, lecturers are left with considerable flexibility regarding practical, i.e. demonstration and experiment process. On the other hand, graduates put different emphases in their education. For example, those who go on to complete a higher degree will typically need a strong foundation in basic scientific principles, whereas those who choose industrial career typically need a greater emphasis on practical relevance.

A well-rounded course in control engineering needs to combine the appropriate theoretical knowledge with a strong emphasis on relevance. Thus, basic theory is best presented in a directed fashion with the going through suitable examples. It means, that lecture courses need to be supported by practical laboratory sessions. However, this leads to a dilemma for educators, namely how to achieve an appropriate tradeoff between cost, flexibility and safety of laboratory. In that way, there has been substantial ongoing interest by engineering educators and education researchers throughout the world. A comprehensive review of the literature relating to hands-on, simulated and remote laboratories is given in [1]. Paper [2] refers constant pressure on universities and the emergence of new technologies in the creation of novel engineering systems in education, especially simulation and remote-access laboratories. Proponents of simulations assert that physical laboratories needlessly consume university space and funds, while advocates of hands-on laboratories argue that students

should be exposed to real environments. Remote laboratories have appeared as a third option. Authors in [3] discuss about factors of a separation, both physical and psychological, between the students and the laboratory hardware and a technology-mediated interface that is used to close this distance.

Practical side of education in control engineering field, especially electrical drive control is one of the most challenging tasks. Modern electrical drives require fast, accurate and robust control system. Powerful digital signal processors (DSP) offer a variety of different functions providing implementation of sophisticated algorithms. These devices have to provide high drive performance regarding many aspects such as accuracy, low energy consumption, safety, motor parameter mismatch and different motor size handling. Given the cost of purchasing, operating and maintaining motor drives, some educators question whether it is actually necessary to have experimental work at all. On the other hand, students strongly perceive the need to relate the theoretical content of their courses to the real world. Therefore, emergence of a highly flexible and safe platform for education is the key driver in courses comprising digitally controlled drives. In that sense, the real-time emulators could be very useful, since they offer motor drives control studying in an effortless manner. They provide variety of different power converter topologies, motor types, power levels, torque load profiles, etc. Considering mentioned, the ultra low latency Hardware-In-the-Loop (HIL) platform has recognized as a high end prototyping tool [4]-[5], which can be successfully utilized for motor drive control development process also [6]-[7].

In this paper, main practical aspects of motor control are shown on the typical and comprehensive example with indirect field oriented control (IFOC) of induction machine drive. Instead of using expensive, inflexible and potentially unsafe real hardware, DSP interacts directly with Hardware-In-the-Loop system. In that manner, all DSP control signals are fed to real-time emulating system comprising power converter and induction machine, while all feedback signals are returned to the controller. In the first part of the paper, sinusoidal and space vector modulation strategy for voltage generation is tested on a emulated three phase resistive-inductive load. Simplicity of the proposed system is then illustrated in the

paper second part in the example of IFOC induction machine drive. For the current and speed control loops, system step responses are shown for a standard parameters selection procedure. Verification of reference frame angle calculation in IFOC case is presented also.

II. EDUCATIONAL SETUP DESCRIPTION

Complete control algorithm is implemented on digital signal processor as in a real environment case, while total power stage is realized on a emulator. Proposed system for the education is shown in Fig. 1.



Figure 1. Educational setup with DSP controller and HIL

Digital signal controller is placed in appropriate docking station which adjust signal levels between it and HIL device. For the motor control and power electronics applications a devoted DSP, having peripherals such as PWM, ADC, quadrature encoder and capture unit is chosen (TMS320F2808, Texas Instruments). DSP software development environment, Code Composer Studio is used for DSP control education purpose. Lego like software blocks (such as Park&IPark transformation, space vector PWM modulation, PI regulator, speed calculation, etc.), written in widely spread "C" programming language are used.

Power stage of the considered scheme, comprising grid voltage, rectifier, inverter and motor is completely emulated in real time on the HIL system. HIL used in this paper is based on scalable, custom, ultra low latency processor design

implemented on FPGA chip. This approach results in I/O latency of the order of $1\mu s$ for the typical two and three-level topology of PE converters. Fidelity confirmation as well as details about power electronics converters modeling used in this HIL platform is based on the work in [8]-[11]. The used HIL platform is flexible enough to cover not only a motor drive, but also a range of power electronics (PE) applications and in this way facilitates rapid system-prototyping. Furthermore, modeling environment, using a graphical user interface is intuitive and easy to use. Software tool-chain consists of the three basic elements, Fig. 2. It includes a schematic editor, where scheme is easily drawn from rich library of predefined switching models of PE elements and linear models of electrical machines, electrical sources, and passive elements. The second part is circuit compiler, which translates schematic in the HIL acceptable format. The third part is emulator control panel which controls emulation during runtime, e.g. its start/stop, change source values/frequencies, open/close contactors, etc. These tools provide a flexible environment for model editing, compiling and running the emulation.

The aim of the described experimental setup is to guide students and researchers in obtaining hands on experience to build, develop and verify control algorithm in a highly flexible and safe manner.

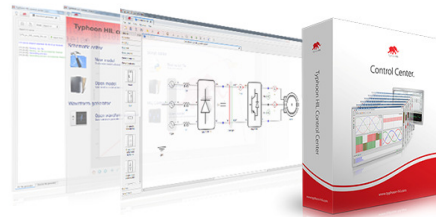


Figure 2. HIL control center toolchain

III. EXPERIMENTAL WORK IN A VIRTUAL LABORATORY

In order to demonstrate effectiveness of utilized system, standard control for the IFOC induction machine drive, shown in Fig. 3, is considered here.

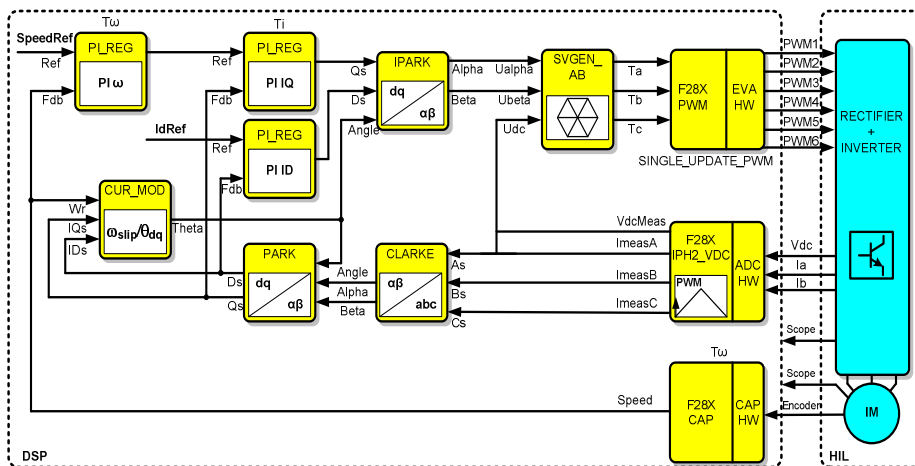


Figure 3. Example: block diagram of indirect field oriented control of induction motor, DSP and HIL side

IFOC is widely used control, based on transformation from stationary to synchronously rotating coordinates which leads to a simple control structure similar to that of a separately excited DC machine. Position of the reference frame tied to machine rotor flux is calculated as integral term of sum of electrical rotor speed and estimated slip frequency.

There are proposed several steps that thoroughly introduce students to the world of digital motor control. In addition to being used for the education, they can be encountered in the industrial environment also. They are summarized in Table I. In the following text, the most significant details of them will be presented.

TABLE I. TEST PHASES OF THE IFOC MOTOR DRIVE CONTROL

Software Module	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
RAMPCTRL	√	√	√	√	√
RAMPGEN	√	√	√	√	√
IPARK	√√	√	√	√	√
SVGEN	√√	√	√	√	√
PWM	√√	√	√	√	√
CLARKE		√√	√	√	√
PARK		√√	√	√	√
CAPTURE			√√	√	√
SPEED_PR			√√	√	√
PI (I _d , I _q reg)			√√	√	√
CURMOD (θ _{dq})				√√	√
PI (spd reg)					√√

Note: the symbol √ means this module is using and the √√ means this module is testing in this phase

The first, usual step in a depicted motor drive control is verification of PWM modulation strategy, no matter which type is used. Although space vector modulation is commonly used comparing to sinusoidal, just for educational reason both will be presented here. For that purpose, block diagram of control code (i.e. DSP side) shown in Fig. 4. is used. Output voltage amplitude is set by constant $V_{dTesting}$ and $V_{qTesting}$ variables, while output frequency is defined by constant $SpeedRef$ value, which is smoothed and transferred to ramp signal by software blocks RAMPCTRL and RAMPGEN, respectively.

Appropriate power stage is emulated on HIL side (Fig. 5): three-phase inverter, DC constant voltage source in converter DC-link circuit, RL load at converter output and some measurement elements for feedback values. In general, additional measurement equipment such as for line voltage measurement and filtering here are not necessary since this signals are automatically present in HIL safe and user friendly environment.

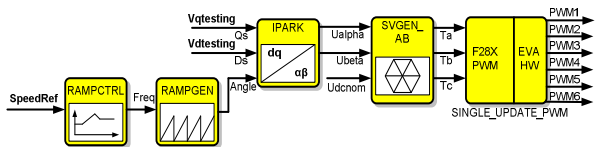


Figure 4. Block diagram of control code for verification of PWM modulation strategy (DSP)

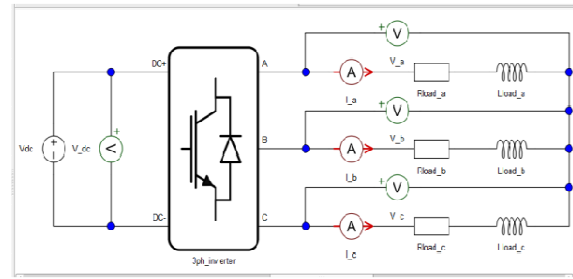


Figure 5. Emulated three phase inverter with RL load (HIL)

Expected load phase current value and load impedance can be calculated as in (1).

$$i_{out}^{amp} = \frac{v_{out}^{amp}}{z_{load}} = \frac{v_{out}^{amp}}{\sqrt{R_{load}^2 + x_{load}^2}} = \frac{v_{out}^{amp}}{\sqrt{R_{load}^2 + (2\pi f L_{load})^2}} \quad (1)$$

In a case of sine PWM modulation strategy, phase output voltage is calculated as in (2).

$$v_{out}^{amp} = mod_{ind} \frac{v_{dc}}{2} \quad (2)$$

For this case, the calculated duty-cycle values for each phase legs and corresponding voltage reference in controller program are shown on the upper part of Fig. 6. On the lower part of this figure, motor phase voltage and currents at HIL output are given (modulation index 0.5, $f = 50\text{Hz}$).

In a case of space vector PWM modulation strategy, we have better utilization of available dc link voltage comparing to sinusoidal strategy. The phase output voltage is calculated as in (3).

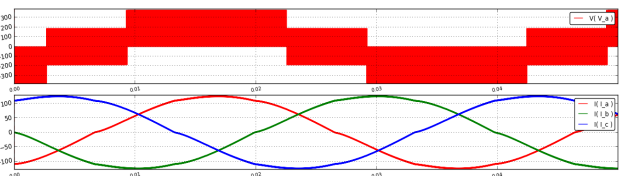
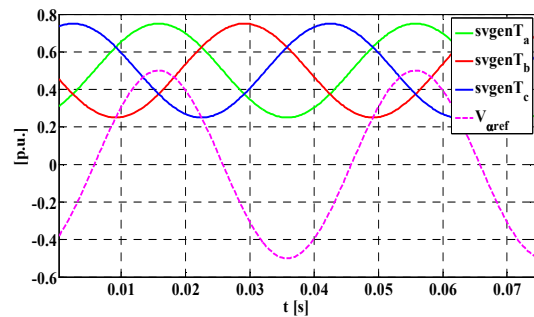


Figure 6. Sine PWM modulator: recorded controller variables (duty-cycle values for each phase legs, voltage reference) and captured HIL model data:

three-phase currents (I_a , I_b , I_c) and phase voltage (V_a) for reference frequency 50 Hz and modulation index 0.5

$$v_{out}^{amp} = \text{mod}_{ind} \frac{v_{dc}}{\sqrt{3}} \quad (3)$$

For this strategy, the calculated leg's duty-cycle values and corresponding alpha voltage reference in controller are shown on the upper part of Fig. 7. On the lower part of this figure, motor phase voltage and currents at HIL output are given (modulation index 0.5, $f = 50\text{Hz}$). One can note that DSP calculated duty-cycle values have typical waveforms which deviates from sinusoidal, with two humps in the area of its maximum and minimum values.

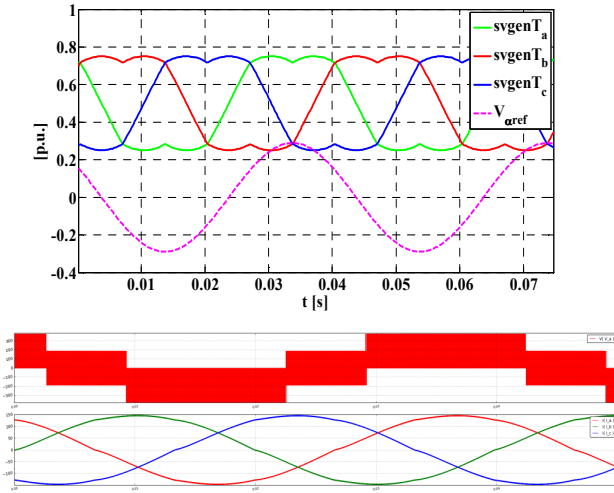


Figure 7. Space vector PWM modulator: recorded controller variables (duty-cycle values for each phase legs, alpha voltage reference) and captured HIL model data: three-phase currents (I_a , I_b , I_c) and phase voltage (V_a) for reference frequency 50 Hz and modulation index 0.5

Both given examples are given for schematic load resistance 1Ω , inductance 1mH and dc-link voltage 563V ($230 \cdot \sqrt{3}$). Therefore, there can be easily verified that inverter current amplitude matches theoretical results, Fig. 6. and Fig. 7.

After successful PWM modulation test, an open loop control of induction machine (Fig. 8) can be easily employed. For the given voltage frequency and amplitude, machine rotor without torque load will rotate at synchronous speed divided by pole pairs number.

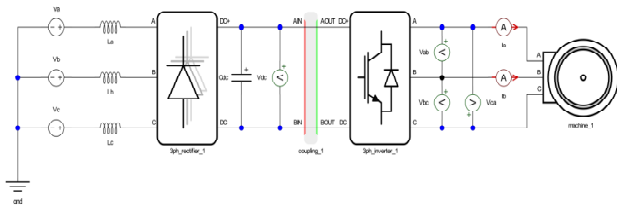


Figure 8. Emulated power stage of motor drive (HIL)

The next important step in motor drive control design is to setup current control loop. In that sense, limits and gains of current loop PI controllers parameter arrangement is the most sensitive task. In order to eliminate side effects, constant DC bus (therefore DC-link voltage ripple is zero), inverter zero dead time and locked rotor (high potential torque load and/or high inertia coefficient) is easily selected in the HIL environment.

According to induction motor voltage and flux equations, expressions for electrical part of the machine in a case of vector control can be obtained (4), (5).

$$U_{sd} = R_s i_{sd} + L_\sigma \frac{di_{sd}}{dt} - \omega_s L_\sigma i_{sq} \quad (4)$$

$$U_{sq} = R_s i_{sq} + L_\sigma \frac{di_{sq}}{dt} + \omega_s L_\sigma i_{sd} + \omega_s \frac{L_m}{L_r} \psi_{rd} \quad (5)$$

After applying decoupling strategy and neglecting the last, slow changing term in (5), current regulation scheme is obtained, Fig. 9. In a case of permanent magnet synchronous machine, parameter L_σ has to be replaced with L_s or L_{sd}/L_{sq} depending on whether the magnets are surface or interior mounted. Similar, in a case of DC machine parameter L_σ should be replaced with armature inductance parameter L_a . Variables denoted with ^ sign are controller side motor parameters, i.e. expected ones. In the case of this HIL utilization, they are set to be equal with real ones, but in general they can be changed easily for test purposes.

Motor current loop response according a number of different procedures for PI regulator parameters can be easily observed. Here, results of one of the most commonly used, Dahlin algorithm [12] is given. For the first order system transfer function (6), where T_i is object time constant (here T_σ) and τ is inverter transport delay (here T_{PWM}), parameters are given in (7) and (8).

$$G_{ob}(S) = \frac{1}{1 + sT_i} e^{-\tau s} \quad (6)$$

$$K_p = \frac{1 - e^{-\lambda T}}{K \cdot (e^{T_i} - 1) \cdot [1 + N \cdot (1 - e^{-\lambda T})]} \quad (7)$$

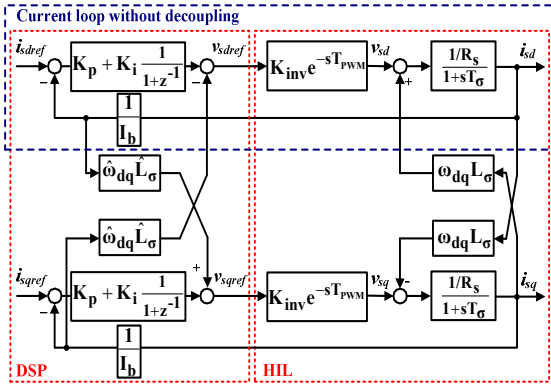


Figure 9. Current regulation scheme

$$K_i^z = K_p \frac{T}{T_i} = K_p (e^{\frac{T}{T_i}} - 1) \quad (8)$$

Total object gain is $K = K_{inv} \cdot (1/R_s) \cdot (1/I_b)$, where is $K_{inv} = V_{dcbus}/\sqrt{3}$ for windings star connection; number of delay periods is $N=1$. Parameter λ defines system response having dominant time constant $T_d = 1/\lambda$ and here is chosen to be $5/T_\omega$ which means that current will achieve reference in one speed period loop (T_ω). For the calculated parameters, $f_{PWM} = 20\text{kHz}$, current loop period $1/4\text{kHz}$ and speed period $T_\omega = 5\text{ms}$, direct axis current step response of the stalled motor is given in Fig. 10, upper part. One can notice that referenced current is achieved without overshoot (aperiodic) and in a expected time of $5 \cdot T_d = T_\omega$ what is in accordance with Dahlin's algorithm. On the lower part of the Fig., zoomed signals of phase current (ripple) and input voltages captured on HIL side are presented.

In a case of induction motor indirect field oriented control with dq coordinate system tied to rotor flux, the next important step is to test the reference frame angle calculation. For calculation of this angle, the fundamental thing is electrical slip frequency estimation, given in (9). According this equation, slip frequency can be easily numerically evaluated for several values of quadrature current i_{sq} under the same condition (locked rotor) for the machine with nominal flux (referenced nominal direct current i_{sdn}). In Fig. 11, motor phase currents and electrical torque for fluxed machine with stepped quadrature current i_{sq} is shown. In this experiment, the same value for both d and q stator current is chosen, resulting that slip frequency is equal to reciprocal of rotor time constant.. Frequency of currents in locked rotor case is the same as calculated DSP slip frequency given in (9), since rotor speed is zero.

$$\omega_s = \frac{L_m}{T_r} \frac{i_{sq}}{\psi_{rd}} = \frac{1}{T_r} \frac{i_{sq}}{i_{sd}} \quad (9)$$

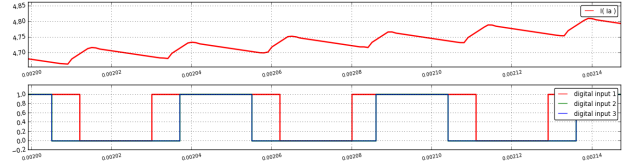
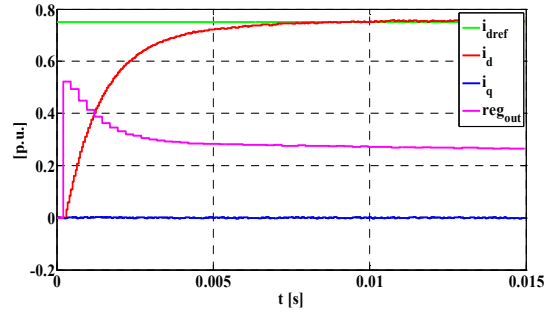


Figure 10. Current step response (0.75 p.u.): controller variables (reference/actual currents and regulator output) and captured HIL model data: phase current and inverter leg voltages (zoomed).

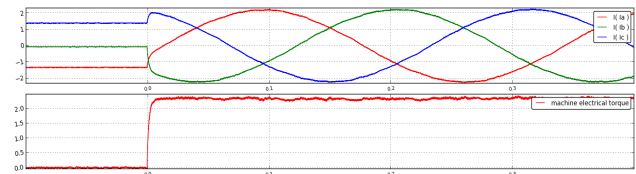


Figure 11. IFOC, dq reference frame angle calculation test (i_q current step 0.2 p.u., constant $i_d = 0.2$ p.u.); captured HIL model data: phase currents and electrical torque.

The last step in drive control design is test of speed control loop. According to block diagram in Fig. 12, parameters of speed PI regulator are calculated [13]. In this case, speed is reached without overshoot and for minimal possible time. Implemented PI regulator has proportional gain in local path in order to avoid abrupt speed variation. Since speed information is averaged per a loop period, measurement transfer function is given as in (10), while gain K_m in vector drive as in (11).

$$W_{meas}(z) = \frac{1+z^{-1}}{2} \quad (10)$$

$$T_{el} = \frac{3}{2} P \frac{L_m}{L_r} \psi_{rd} i_{sq}^{[A]} = \frac{3}{2} P \frac{L_m^2}{L_r} i_{sd}^{[A]} I_b i_{sq}^{[rel]} = K_m i_{sq}^{[rel]} \quad (11)$$

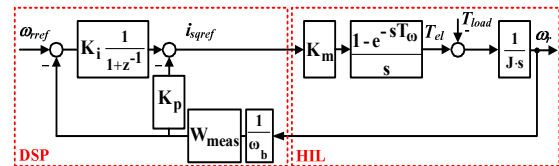


Figure 12. Speed regulation scheme

Speed step response is shown in Fig. 13. This results are completely in accordance with theoretical expectations also.

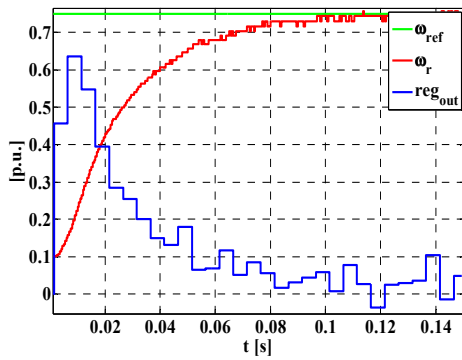


Figure 13. Speed step response (0.75 p.u.): controller variables (reference/actual speed and regulator output) and captured HIL model data: speed, phase currents and electrical torque, respectively

IV. CONCLUSION

This paper discussed how to overcome gap between basic theory on the one hand and engineering design reality on the other. The paper identified one efficient solution for bringing students closer to reality by the use of emulation based virtual laboratory. This type of laboratory gives students exposure to the reality of industrial control system design in a structured and user-friendly environment. Using Hardware-in-the-Loop system, students are capable to learn, test and verify every aspect of their control procedure. Beside great flexibility, this proposed system presents highly safe environment. In that manner, it allows user to completely focus on software-based functionalities without any hardware concerns.

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