Arthur Hermano Rezende ROSA, Reginaldo Vagner FERREIRA, Cláudio Alves PEREIRA*

Instituto Federal de Minas Gerais - Campus Betim, Graduate Program in Teaching - Instituto Federal de Minas Gerais - Campus Arcos*, Brasil

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Integrated PBL and HIL practices for real-time simulations applied in technical and engineering teaching using embedded systems

Abstract. *Many educational institutions do not have sufficient resources to acquire expensive devices to make the dialoged and practical classes more attractive, both for students and for teachers. In view of these concerns, it is proposed a procedure that integrates PBL (Problem based Learning) and HIL (Hardware in The Loop) methods to test different dynamic systems, verify stability of the implemented control equations, or even validate useful algorithms in many areas, from basic disciplines of Exact Sciences to Technical and Engineering courses. The conception approach is presented here to justify the best possible cost-effectiveness benefits to simulate real-time systems, with financial and time reductions. The project consists of developing three prototypes (heat exchanger, electronic converter and "Beam and Ball" experiment) by means of a mathematical modeling using the Matlab / Simulink software, to embedded this model in a HIL hardware in order to simulate / diagnose the performance of such systems. These examples can be used in both practical and theoretical classes, in order to encourage students to deal with real problems in search of their solutions.*

Streszczenie. *Wiele instytucji edukacyjnych nie ma wystarczających środków na zakup drogich urządzeń, które uczynią prowadzone z dialogiem i zajęcia praktyczne bardziej atrakcyjnymi zarówno dla uczniów, jak i nauczycieli. W związku z powyższym proponuje się procedurę integrującą metody PBL (Problem based Learning) i HIL (Hardware in The Loop) w celu testowania różnych układów dynamicznych, weryfikacji stabilności zaimplementowanych równań sterowania, a nawet walidacji użytecznych algorytmów w wielu obszarach, od z podstawowych dyscyplin nauk ścisłych po kursy techniczne i inżynierskie. Przedstawione jest tutaj podejście koncepcyjne w celu uzasadnienia możliwie najlepszych korzyści w zakresie efektywności kosztowej symulacji systemów w czasie rzeczywistym, przy jednoczesnym ograniczeniu finansowym i czasowym. Projekt polega na opracowaniu trzech prototypów (wymiennik ciepła, przetwornik elektroniczny i eksperyment „Belka i kula") za pomocą modelowania matematycznego z wykorzystaniem oprogramowania Matlab / Simulink, w celu osadzenia tego modelu w sprzęcie HIL w celu symulacji / zdiagnozowania działania takiego systemy. Przykłady te można wykorzystać zarówno na zajęciach praktycznych, jak i teoretycznych, aby zachęcić uczniów do rozwiązywania rzeczywistych problemów w poszukiwaniu ich rozwiązania.**(Zintegrowane praktyki PBL i HIL do symulacji w czasie rzeczywistym stosowane w nauczaniu technicznym i inżynieryjnym z wykorzystaniem systemów wbudowanych)***

Keywords: PBL , HIL, SFL, teaching, SEPIC, ball beam, heat exchanger
Słowa kluczowe: PBL, HIL, SFL, nauczanie, SEPIC, belka kulowa, wymiennik ciepła

Introduction

The technology has broken several paradigms and has changed many workstations. Continuous changes in society, economics and technology - in the fourth industrial revolution context - are evident when we observe apps for transport, e-commerce, softwares for legal sector, remote support, biomedical devices, among many other examples of our new day-to-day [1], [2]. In a not very different situation is education system, which is subjected to the technology revolution. New technology resources enable innovative methods that tend to be more enjoyable, both for students and teachers, in order to streamline and facilitate the teaching and the learning process.

In this context, PBL (Problem based Learning) practices have been highlighted, in which the main objective is to improve the learning through proposed problems to students [3]- [4]. Here we have a challenge: the teachers need to be creative, while schools and universities need to invest in equipment capable of contextualize the theories and concepts learned in the classroom.

Some systems and equipment are expensive for teaching institutions, that often make it impossible to use them in class. When performing HIL (Hardware in the loop) techniques and embedded systems it becomes possible to build part of the real system (for example the controller) and to use the high cost part of the system (the plant) in a real time simulator. In other words, practical demonstrations are used to facilitate the learning process through low cost setups. The objective of this work is to integrate real time simulation methods with PBL practices, especially HIL techniques.

The project consists of developing three prototypes: heat exchanger, electronic converter and Ball and Beam experiment. A mathematical modeling is developed in Matlab/Simulink software and it is embedded in a hardware in the loop, aiming to emulate the behavior of such systems. These prototypes are used in both practical and theoretical classes (PBL classes).

The specific objectives are:

- apply functions (control algorithms) in Matlab and real time simulators;
- project controllers in embedded systems;
- apply control techniques for instrumentation, mechanics, physics and science.
- familiarize students with the plant, simulations and plant modeling;
- perform HIL simulations, in which a part of the system is real (not only simulated);
- contextualize the problem to the student and interact the student to the problem through practical examples;
- employ the method in Basic, Technical and Technological Education (EBTT) and in the embedded systems, control and automation laboratories.

This paper is organized as follow: chapter 2 describes the proposed methodology, chapter 3 is dedicated to case studies and results to exemplify the application of the method, and finally, in chapter 4 are presented the conclusions and final remarks.

Methodology: HIL + PBL

The fast advance of digital and embedded systems has allowed the use of such systems in different applications [5]. Although it is still little explored, hardware in the loop represents a potential application area, in which the software and hardware can be evaluated. Real Time Simulation (RTS) methods also demonstrate feasibility for teaching applications, for example to verify the performance and stability of dynamic systems. Commercial solutions, as OPAL-RT, that presents high cost and sophistication are widely available [6]. Examples of digital real-time simulators (DRTS) with high precision in their results are: TYPHOON HIL [6], OPAL-RT [7], dSPACE [8] e RTDS [9]. On the other hand, a less complex real-time simulation platform than previously mentioned may be desirable. In this sense, the use of sophisticated and

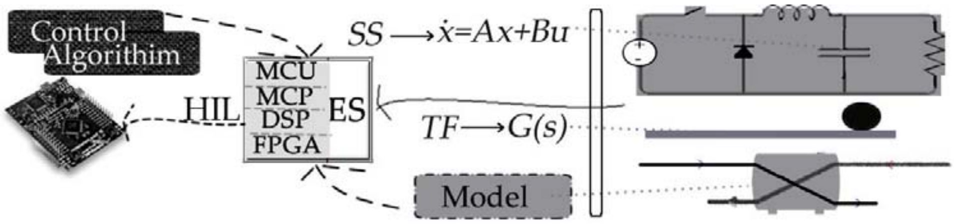

Fig. 1. Proposed methodology

high-cost computing devices is not always justified. In addition, the fact that many educational institutions around the world do not have sufficient resources to acquire expensive equipment, such as the industrial heat exchangers discussed in this work.

In view of these concerns, this work proposes a procedure that integrates PBL and HIL methods to test the dynamics of different systems, verify the stability of control equations, or even, validate algorithms used in different areas. The proposal can be applied in basic subjects of exact sciences, technical courses and engineering undergraduate courses. The approach is designed to justify the cost benefit needed to simulate the systems in real time, with less financial expenditure and time spent on execution.

Figure 1 shows an overview of the proposed methodology. The first step is to obtain the mathematical models of the plant, control equations and other needed algorithms. These models can then be simulated using software such as Matlab, Scilab or Labview [10], [11], [12]. After implementation, it is necessary to run the simulation and check if the variables are converging to the desired steady state. When this is achieved, the next step is to incorporate the simulated system into the embedded system (ES). Using Simulink / Matlab external mode and a E compiler, the model will be converted in codes and after loaded into the hardware. Finally, the ES will runs the code, emulating the physic system and control algorithms. As shown in Figure 1, some considerations are important:

1. the embedded system (ES) can model and replace only the system;
2. it is possible to model only the control algorithm, if it is desirable;
3. the modeling can be a transfer function (TF) using Laplace or z transform (discrete case), description in the State Space (SS), or other types such as non-linear models (ex: Euler-Lagrange);
4. the proposal is applicable in control, instrumentation, modeling, or even, any algorithm to solve any problem, mainly in exact sciences. It is possible to expand the use of the method to other areas (ex.: modeling of a human biological system);
5. the embedded system (ES) can be a micro-controller (MCC), a digital signal processor (DSP), a Field Programmable Gate Array (FPGA) or a microcomputer (MCP). In this work, it is recommended the DSPs, that have the best cost-benefit, because even though they are cheap, they can perform relatively complex functions. On the other hand, MCCs are recommended for simpler systems, FPGAs and MCPs for more complex systems [13], [14].

In order to illustrate the application of the proposed method, the Ball & Beam experiment is used, as one can see in Figure 2, where the main quantities are listed in Table 1.

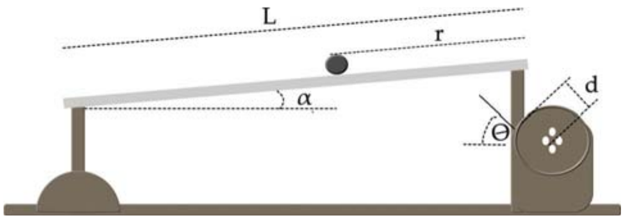

Fig. 2. *Ball & Beam* experiment

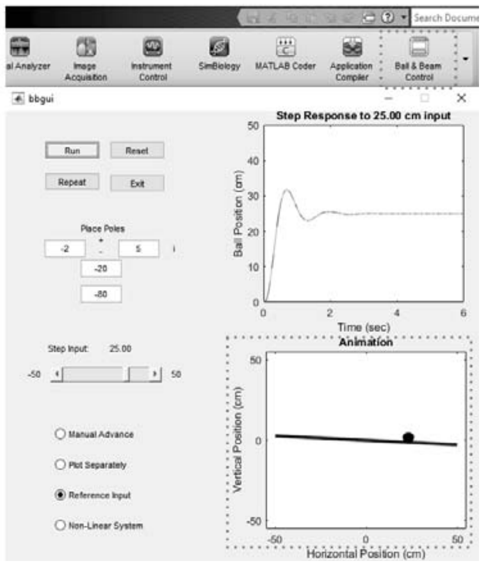

Fig. 3. Ball and Beam simulation. In the app “Ball & Beam Control”, that can be downloaded and installed online, it is possible to adjust the control gains, the initial values and the set-points, in addition to the animation of the system.

The transfer function of the plant [15] is given by:

$$G(s) = \frac{R(s)}{\Theta\ (s)} = -\frac{mdg}{L\left(\frac{I}{{R_b}^2} + m\right)s^2}. \tag{1}$$

After modeling, it is proceeded the system simulation (for more details, please consult the works developed in [15] and [16]). In the Matlab software, just click in “Apps” and, then, “Ball and Beam Control”, as shown in Figure 3:

After the simulation, the model (transfer function) and the controller (PID - proportional integral derivative) are embedded into the DSP 28377s from Texas Instruments, as can be seen in Figure 4. In this case study, the objective of the

Table 1. **Quantities of the *Ball & Beam* experiment**

Quantity	*Description*	*Value*
m	ball mass	0.11 kg
R_b	ball radius	0.015 m
d	lever shift	0.03 m
g	gravitational acceleration	9.8 m^2
L	beam length	1.0 m
I	moment of inertia of the ball	$9.99e^{-6} kgm^2$
r	ball position	
α	beam angle	
θ	servomotor gear angle	

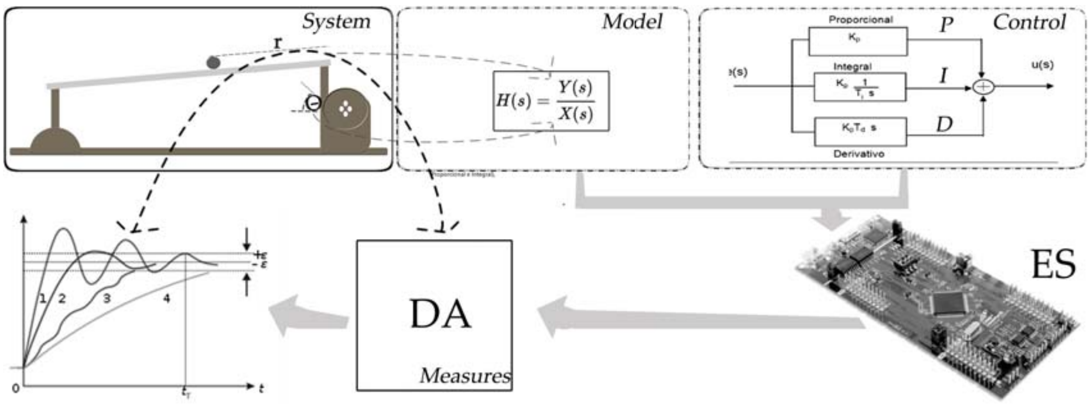

Fig. 4. Ball and Beam HIL simulation

Table 2. **Softwares and *Hardwares* recommended**

Type	Software / Hardware	Justification
Simulation Software	Matlab / Simulink	Full Software, generally with available licence in the educational institution
Embedded System	C2000 Delfino DSP TMSF2837x LaunchPad	Low cost DSP and development kits with high processing power
Oscilloscope	OscBox Bluetooth DSO OPX-1600, 2 Ch, 12 MHz, 50 MS/s	Suporte Bluetooth, light, small and compatible with smartphone
App for *Ball & Beam* simulation	*Ball & Beam*	App developed for Matlab
Heat Exchanger Temperature Control	*Heatex*	Example available on Matlab

control is stabilize the position of the ball *r* in a certain fixed position (generally in the center of the beam). Depending on the controller gains, oscillations can occurs before reaching steady state.

Figures 5 and 6 shows the output (position) as a function of the time, using a PID controller, in which the *r* value varies from 0 to 20 cm (stability).

The difference between Figure 5 and 6 is that the first was obtained from a conventional Matlab simulation while the second is processed in a HIL simulation and measured using a digital-analog converter (DAC). This last is done by programming the DSP pins through the DAC blocks (Digital Analog Converter) available in the C2000 Texas Instruments package and checking the desired signals in an oscilloscope. A digital oscilloscope with *bluetooth* support is recommended, because besides being lighter and easier to carry, they are cheap and compatible with smartphones [17]. Table 2 summarizes the softwares and hardwares recommended, including the justification of each one.

It is important highlight the need for a calibration adjustment to match the measurement range between the simulation and the ES used in HIL (in this case, for *r* equal to 20cm, the digital value measured at the DA converter output corresponds to 2000). Since the resolution of the DA converter is 12 bits, the maximum measured value is 2^{12} = 1096, that

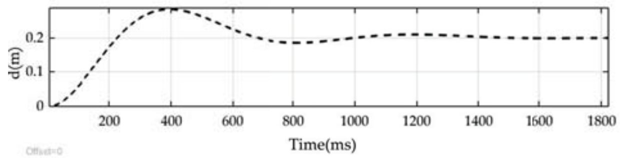

Fig. 5. Closed loop response of *r* in a conventional Matlab simulation.

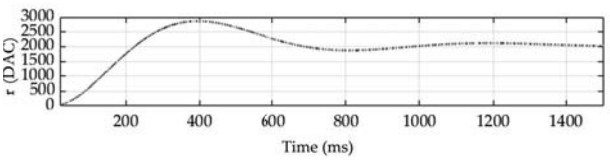

Fig. 6. Closed loop response of *r* in the HIL simulation.

correspond to 40.96cm. In addition, models and equations must be discretized so that the embedded digital system can compute the necessary equations.

Case study

Three case studies were selected: *Ball & Beam* experiment (already discussed in the previous section), heat exchanger, and power electronic converter. The courses, field of knowledge, models and algorithms related to each case study are shown in Table 3.

Case Study 1: Heat exchanger

Problem Description

In Oil and Gas Treatment Units and in many other types of industries (example: food industry, refineries, marine platforms, steel mills, etc) it is necessary to detect and to correct possible irregularities in systems and equipment. Such failures cause a reduction in the efficiency of the plant and, consequently, result in a higher operating cost. As an example of a relevant problem, we can mention the fouling process that occurs in heat exchangers.

Over the years of use, the residues that accumulate inside these devices cause them to clog, which drastically reduces their performance. In oil extraction and treatment platforms, heat exchangers are essential elements to heat crude oil and facilitate the water withdrawal process. The low efficiency of these devices can compromise the optimal functioning of the petrochemical plant as a whole.

Generally, this problem is detected in a simple way through the local inspection of the equipment, or even through the simplified analysis of the process variables. Periodically and by means of local meters, the field operator obtains the differential pressure data between the upstream and downstream of the exchangers, passing on such information to the responsible engineering team. With the differential pressure measurement it is possible to evaluate the efficiency of the exchanger, or in other words, if the pressure is high, there is a strong indication of clogging. Another method of evaluate this problem is the analysis of graphs, especially

Table 3. **Case Studies**

Case Study	*Course*	*Field*	*Model*	*Algorithm*
Heat exchanger	Technician /Higher Education	Instrumentation, Control, Mechanics	Efficiency and Performance	Fault detection and diagnosis
Ball and beam	Basic/ Technician /Higher Eduction	Modeling, Instrumentation, Control, Physics	Transfer Function	Measure and linear control
Electronic converter	Technician /Higher Education	Control , Electronics, Electricity, Renewable Energies	State-Space	Nonlinear control

those involving temperature, since temperature differences between the input and output close to zero represent the possibility of failure. Thus, the monitoring of the current state of the heat exchangers, in most cases, does not occur in real time, which makes engineering decisions difficult. In this sense, a method for detecting failures in heat exchangers is proposed and detailed in the following sections.

Modeling and efficiency of heat exchangers

A heat exchanger is a device for efficient heat transfer between environments with different temperatures. In petrochemical processes, such devices are placed at specific points (usually connected to the side outputs of the reservoirs) to smooth the heat transfer and keep the flow constant.

As shown in Figure 7 and steady-state configuration of the exchanger, we obtain the following expressions:

(2) $$Q_f = F_f C_f (T_{fo} - T_{fi})$$

(3) $$Q_q = F_q C_q (T_{qi} - T_{qo})$$

where : Q_q and Q_f are the average heat transfer rates of the hot and cold fluids, respectively; F_q and F_f are the mass flow rates of the hot and cold sides; C_q and C_f are the specific heats T_{fi} and T_{fo} are the inlet and outlet temperatures of the cold fluid; T_{qi} and T_{qo} are the inlet and outlet temperatures of the hot fluid.

More details of exchangers modeling can be seen in [18] and [19] . In ideal situations the values Q_q and Q_f tend to be the same, which means that the energy supplied by the hot current it is totally absorbed by the cold side. Therefore, the ratio between the heat transfer rates is given by:

(4) $$R_q = \frac{Q_f}{Q_q}$$

can be used as performance indicator of heat exchangers.

A generic countercurrent exchanger is considered to have two sides on which hot and cold fluid enter or exit as seen in Figure 7 . In view of certain operating conditions - such as the constant total heat transfer coefficient and the constant specific heat and disregarding heat losses - the LMTD is defined by the logarithmic average as follows:

$$\Delta T_1 = (T_{qi} - T_{fo}), \Delta T_2 = (T_{qo} - T_{fi}),$$

(5) $$LMTD = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

Fig. 7. Energy transfer in heat exchangers.

Thus, LMTD is commonly used to estimate the overall heat transfer coefficient, which corresponds to an intrinsic characteristic of the device to determine the total heat transfer between the two currents, hot and cold. Therefore, the basic equation for a heat exchanger is given by:

(6) $$Q_{f,q} = UA(LMTD)$$

where :

Q_q e Q_f are the average heat transfer rates of hot and cold fluids (equal under ideal conditions);

A = heat transfer surface area (m²);

U = overall heat transfer coefficient (W/m²°C);

LMTD = Log Mean Temperature Difference (°C).

From expression (6) and isolating the terms that depend on the physical characteristics of the exchanger (*UA*), we obtain:

(7) $$UA = \frac{Q_{f,q}}{LMTD}$$

By considering the constant area and different hypotheses:

1. if the value of the flows F_f or F_q increases, the value of $Q_{f,q}$ increases, the value *LMTD* also increases;
2. if the temperature differences between the inlet and outlet fluids increase or decrease, the values $Q_{f,q}$ and *LMTD* proportionally change
3. *U* and *LMTD* values are inversely proportional

Normally, flow rates remain constant, small changes in these variables occur due to changes in the point of operation of the plant, although greater care must be taken in relation to differences in inlet and outlet temperatures, which may be due to fouling process.

Algorithm

By considering the works referenced in [19] and [20], we propose a fault detection algorithm of heat exchangers (where the four temperature measurements and the two flow measurements are known). As shown in Figure 8, the following steps are considered:

Step 1 – Measurement status:

Test if the instrumentation is working correctly using the following relationship::

(8) $$R_2 = \frac{F_f}{F_q} = \frac{c_q(T_{fo} - T_{fi})}{c_f(T_{qi} - T_{qo})} > Thr$$

According to the scheme depicted in Figure 8, when this value exceeds the pre-established threshold, there are possible measurement failures.

Step 2 – Check the evolution of the Q_f, Q_q , $UA_{f,q}$ and process variables, as shown in (8-B). If there are few significant variations close to the nominal conditions, the exchanger is operating at normal mode. In possible fault conditions the values $UA_{f,q} = \frac{Q_{f,q}}{LMTD}$ tend to follow the fall in

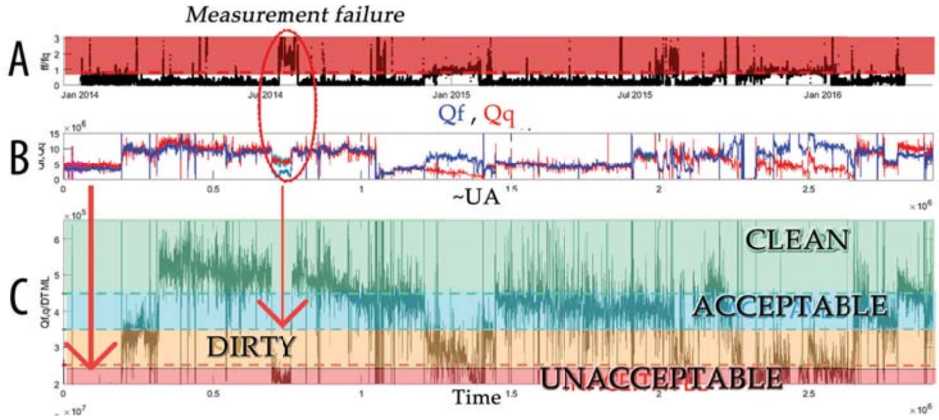

Fig. 8. Steps of the proposed algorithm

Q_f or Q_q. Consequently, the efficiency decreases, since difference between inlet and outlet temperatures are difficult to maintain.

Step 3 – Obtain the UA_n value that corresponds to the product of the overall coefficient by the area of the clean exchanger, as a function of nominal values (Q_n and $LMTD_n$) according to the design specifications:

$$UA_n = \frac{Q_n}{LMTD_n} \tag{9}$$

Step 4: Fouling detection is achieved by processing the ratio $CF = \frac{\sim UA}{UA_n}$ (Figure 8-C):

1. $CF > 0.88$: clean,
2. $0.76 < CF > 0.88$: acceptable,
3. $0.64 < CF > 0.76$: dirty,
4. $CF < 0.64$: unacceptable.

Step 5 - Check if there is a sudden drop in flow (eg: greater than 50 per cent). If so, the performance will decreases, which implies in stopped plant condition.

In addition, the design parameters are shown in Table 4. By using Table 4 and applying Equation (9), we obtain the nominal value of UA_n = 283 kWm2/°C.

Simulated results

As shown in Figure 9, the diagnostic results of the exchanger in a given period are obtained using the Matlab software and the modeling discussed in this section. Note that for P1 to P2 period, the exchanger has an unacceptable status, and in the period from P3 to P4, the exchanger is clean.

HIL Results

Figure 10 shows the fouling detection of the E-T1 exchanger (Table 4) using the HIL environment over a two-day period. In this time period, the exchanger presents an acceptable status.

Table 4. Design specifications of E-T1 heat exchanger

	Unity	*Hot side*	*Cold side*
Fluid		Crude oil	Crude oil
Density (d_q,d_f)	Kg/m^3	888.3	920.0
Specific heat (c_q,c_f)	kJ/(kg*K)	2.07	2.13
Mass flow (F_q,F_f)	Kg/h	568900	632700
Input temperature (T_{qi}, T_{fi})	°C	120	55.1
Output Temperature (T_{qo}, T_{fo})	°C	89	82.2
Nominal average heat transfer rate (Q_n)	kW	10160	
$LMTD_n$	°C	35.81	
Area	m^2	1183	

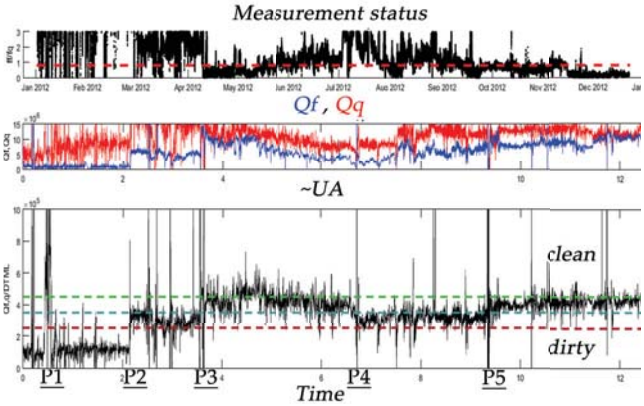

Fig. 9. Data simulation of E-T1 heat exchanger

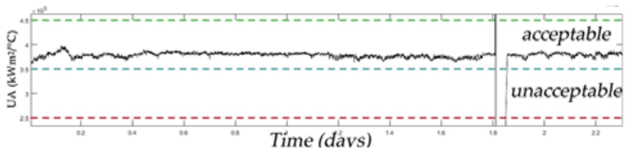

Fig. 10. Global coefficient x Area (UA) of the exchanger estimated in HIL

SEPIC converter

As a final example to illustrate the application of the current method, we chose a converter widely used in renewable energies [21] : the SEPIC converter (Single-ended Primary Inductor converter). Figure 11 shows a typical SEPIC schematic, which output voltage can either increase or decrease in relation to the input.

Based on the works of [22] and [23], the average models described in State Space (SS) and nonlinear control laws of the SEPIC converter are obtained. Note in models described by Equation (10), x_1 and x_3 are the average currents on inductors L_1 and L_2, x_2 is the output voltage in C_0 capacitor and x_4 is the voltage on capacitor C_1, d is the duty cycle and E is the input volage, $G = 1/R$ is the load conductance and V_d is the desired value of the output voltage at resistor load R.

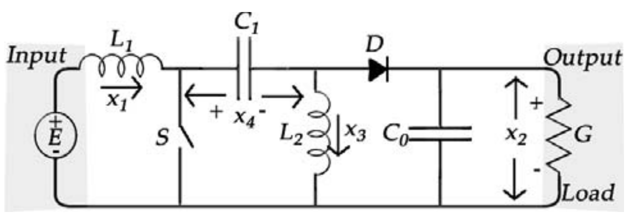

Fig. 11. SEPIC converter

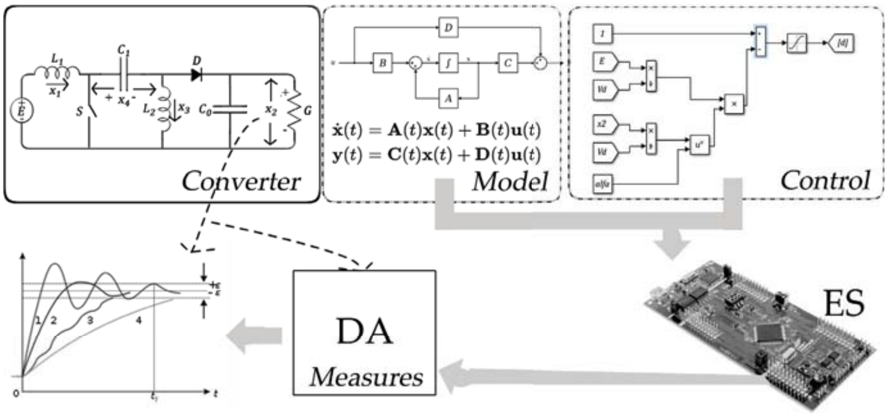

Fig. 12. HIL simulation of the SEPIC converter

SS Model:

$$L_1\dot{x}_1 = E - (1-d)(x_2 + x_4),$$

$$C_0\dot{x}_2 = (1-d)(x_1 + x_3) - \frac{1}{R}x_2,$$

$$L_2\dot{x}_3 = dx_4 - (1-d)x_2,$$

$$C_1\dot{x}_4 = (1-d)x_1 - dx_3. \quad (10)$$

SFL nonlinear control

The SFL (State Feedback Linearization) control law reported in [24] is given by:

$$d = \frac{-R_1(x_1 - x_{1d}) + x_2 + x_4 - E}{x_2 + x_4}$$

$$x_{1d} = G\frac{V_d^2}{E},\ R_1 --> gain \quad (11)$$

In this section, the digital simulations using Matlab and SEPIC converter are presented, implemented according to the design specifications (Table 5) and the SFL control law.

Thus, as shown in Figure 12, the control and state equations are implemented in the Matlab / Simulink environment

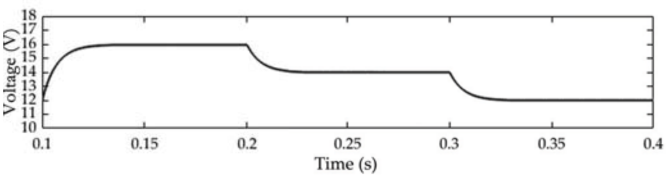

Fig. 13. Capacitor output voltage for SFL control of SEPIC converter - Matlab simulation

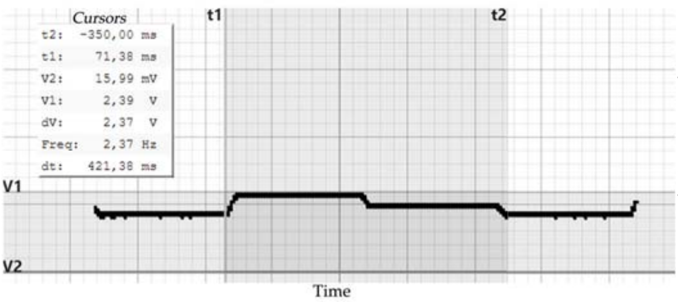

Fig. 14. Capacitor output voltage for the SFL control of the SEPIC converter - HIL simulation. Note: 0.1 s / div on the x axis; on the y axis a 2.4 V in DA converter corresponds to 16V of the real voltage.

Table 5. SEPIC design parameters

Parameter	Value
R	12 Ω
L_1,L_2	2,3 mH
C_1,C_0	470 µF
E	20 V
V_d	12 V
Pout	7,2 W
f	50 kHz
R_1	3

and directly incorporated into a C2000 F28377 Texas Instruments device, through the Simulink Embedded Coder libraries. First, the converter model is developed (usually described by state-space equations as seen in Equation (10)). Then, the duty cycle d - Equation (11) - is calculated for input control.

Figure 13 (Conventional Simulation) and Figure 14 (HIL Simulation) show the responses of capacitor output voltage, taking into account variations of the reference V$_d$ (16 - 14 -12 V).

Conclusions

This article presents the development of a semi-experimental HIL platform for teaching instrumentation / control / electronics that can be introduced in basic, technical and higher courses (Table 3). Three case studies ("ball beam", heat exchanger and SEPIC converter) were built to illustrate the application of the method, both in practical and theoretical classes. In addition, the proposed devices (Table 2) present low cost and easy mobility. A disadvantage is the need of Matlab or similar software instalation.

Given the importance of using hardware-in-the-loop simulations as a propitious educational tool in order to reduce time and costs, we extended the application of the technique in two case studies that can be costly to be acquired by the educational institution : SEPIC converters and heat exchangers. A simple example like "ball and beam" system is also shown in order to demonstrate the extensive applicability of the method.

In the present manuscript, an initial study and a simplified algorithm are proposed to detect failures in heat exchangers that have all the input and output measurements of temperatures and flow rates of hot and cold fluids. As shown in Figure 2, the ratio $UA{=}\frac{Q_{f,q}}{LMTD}$ can be compared with the nominal UA value of the heat exchanger, and the ratio CF = $CF{=}\frac{\sim UA}{UA_n}$ makes it possible to determine different regions of the exchanger operation.

In addition to the unavailability of the real plant, the advantages offered by the method are:

1. There is no need for high cost RTS systems, such as

OPAL-RT, Typhoon HIL, dSPACE and RTDS.

2. The method can be used remotely (using only embedded systems and notebook).
3. It is possible to use the technique for simple applications (eg: plant modeling).
4. Complex systems, such as dynamic systems with extensive number of variables and nonlinear control, can also be tested in software and hardware (at least the controller).
5. Possibilities for gains in teaching and learning.

Authors: *Ph.D. A. H. R. Rosa, Ph.D. R.V. Ferreira, M. C. A. Pereira*, Instituto Federal de Minas Gerais - Campus Betim , Rua Itaguaçu , 595 - Bairro São Caetano - Betim, CEP 32677-562; Graduate Program in Teaching - Instituto Federal de Minas Gerais - Campus Arcos*, Minas Gerais - Brasil; emails: arthur.rosa@ifmg.edu.br, reginaldo.ferreira@ifmg.edu.br,claudio.pereira@ifmg.edu.br.*

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