Low-cost Arduino-based Hardware-In-the-Loop Platform for Simulation and Control of Dynamic Systems

Yineth Martinez-Armero, Sebastian Lopez-Blandon, Eduardo Giraldo

Abstract—**This work proposes a low-cost Arduino-based methodology for simulation and control of dynamic systems. The proposed methodology allows the real-time Hardware-In-the-Loop simulation of multivariable systems and the evaluation of multivariable control techniques. In order to obtain a HIL simulation, two Arduinos are interconnected. One Arduino is used to simulate the plant, and the other is used to implement the controller. In order to evaluate the performance of the proposed methodology, three multivariable dynamic systems are simulated in real-time: an RLC system, a twin rotor MIMO system, and a microgrid. A state feedback controller by using a state observer is used to implement the controller over each dynamic system. An additional I+PD control structure is also used to compare the state feedback control method. An additional software is designed to display the data in a graphical interface in real-time and to analyze and evaluate the performance of each proposed plant and controller.**

Index Terms—**HIL, State-space control, Dynamic Systems, real-time.**

I. Introduction

CURRENTLY, there are different methods and techniques for controlling dynamic systems. Hardware-In-the-Loop (HIL) simulation has become a required method to evaluate and test new prototypes of different types of systems without requiring a prototype construction and bridging the gap between simulation and real conditions [1]. As a result, the proposed controller design can be evaluated over a system replicating real operating conditions. It also can be optimized to reduce the cost and the time before the construction of a prototype to market. This HIL trend has created sophisticated and complex simulation tools for many study areas, usually costing thousands of dollars.

Conversely, Arduino is a free, open-source hardware platform that has recently become intensely important in engineering education because of its versatility, popularity, and low price. Arduino was born in 2005 at the IVREA Institute (Italy) as a student project run by Massimo Banzi, who applied the concepts of accessible hardware and software, which meant a significant change. Currently, there are several types of Arduino boards with different processors, sizes, and connectivity [2]. In [3], an Arduino-based control prototype is proposed for real-time embedded control of a ball and plate multivariable system, where several linear and nonlinear control techniques are evaluated.

The most widely used controller in the industry is the PID controller, which provides a control strategy that can reject disturbances of the unmeasured load at the input of the process. The PID controller was an essential element of early governors. In process control today, more than 95 percent of the control loops are PID or PI type. The PID controllers are today found in all areas where control is used. They have survived many technological changes, from mechanics and pneumatic to microprocessors via electronic tubes, transistors, and integrated circuits. Most PID controllers are designed to respond to changes in the reference point and disturbances at the output of the process. The PID must be tuned to meet objectives such as minimizing integrated peak errors for load disturbances, minimizing set-point overshoot, or time to reach the reference point [4]. The microprocessor has had a dramatic influence on the PID controller. Practically all PID controllers made today are based on microprocessors [5]. One of the main benefits of control systems is the ability to achieve precise and stable performance in various industrial applications, such as factory automation, chemical process regulation, and aircraft flight stabilization. They are also used in transportation systems, such as automobiles and trains, to improve their safety and efficiency. In addition, control systems have applications in everyday life, such as temperature control in homes and speed control in household appliances [1].

Another essential control technique is the control based on state-space feedback. It can generally be represented in equations involving vectors and matrices [6]. Characterizations of this type are usually based on so-called state-space methods. They are an established framework for analyzing stochastic and deterministic dynamical systems measured or observed through a stochastic process. This highly flexible paradigm has been successfully applied in engineering, statistics, computer science, and economics to solve various dynamic systems problems [7].

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Manuscript received March 24, 2023; revised September 5, 2023. This work is funded by project no. E6-23-2 entitled “IDENTIFICATION AND CONTROL OF LARGE-SCALE INTERCONNECTED SMART GRID” by Universidad Tecnológica de Pereira, Pereira, Colombia.

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control systems have applications in everyday life, such as temperature control in homes and speed control in household appliances [1]. The adaptive control strategies allow continuous updates of the system parameters and the design variability in the identified model [8]. The control of systems with non-linearities around an operational point can also be performed by adaptive linear control techniques [9], [10] or by intelligent neural networks-based control [11]. In [12], an ARMAX-based methodology for identifying and controlling multivariable time-varying systems is proposed based on a pole placement technique. The multivariable system can effectively track any set point under noise conditions. However, the model is designed only for systems with equal inputs and outputs.

Kalman filtering is a state estimation technique widely used in electrical engineering. This technique is based on statistical models and uses measurements to estimate the state of a dynamic system, thus allowing the prediction and control of their behavior. With this, the power of a load that is connected to the microgrid can be estimated by measuring voltage and current, which can compensate for the effects of disturbances [13].

The interconnection of microgrids is a research topic of great interest due to the growing need to integrate various renewable energy sources into the electrical grid [14]. In order to achieve an efficient interconnection, it is necessary to develop control and communication techniques that allow the coordination of the different elements of the network. The great challenge is coordinating elements such as generation and consumption and allowing an efficient and stable interconnection [15].

This work proposes a low-cost Arduino-based methodology for the design of control and HIL simulation of interconnected multivariable dynamical systems. Two control techniques are implemented. Three multivariable dynamic systems are simulated in real time: an RLC system, a twin-rotor MIMO system, and a microgrid. The designed software allows us to see the results of the simulations and controls in real-time, which helps analyze and evaluate the performance of each proposed plant and controller. In order to obtain a HIL simulation, two Arduinos are interconnected. One Arduino is used to simulate the plant, and the other is used to implement the controller. The goal is to implement a specific microgrid platform and simulate and evaluate it in real-time using real-time simulation and closed-loop hardware to evaluate interconnection behavior at real conditions, as proposed in [16]. This paper is organized as follows: section II presents the models, the controllers' gains, and the HIl structure. In section III are presented the experimental and simulated results, and finally, in section IV are presented the conclusions and future works.

II. Theoretical Framework

A. State space control

The state space model is widely used in control theory and systems engineering to describe complex systems, such as electrical systems, process control systems, transportation systems, and many others. By using the state space model, an accurate and complete mathematical representation of the dynamic system being modeled can be obtained in (1) and (2).

$$\dot{x} = Ax(t) + Bu(t) \tag{1}$$

$$y(t) = Cx(t) + Du(t) \tag{2}$$

The general equation of the controllability vector is given by:

$$\zeta = [B \ AB \ A^2B \ . . . \ A^{N-1}B] \tag{3}$$

$$rank(\zeta) \geq N \tag{4}$$

where the system is controllable if the $rank(\zeta)$ is greater or equal than N, as shown in (4). Taking into account this property, for a single-input single-output system, the Ackerman equation (5) can be used to find the feedback controller matrix.

$$K_g = [0 \ 0.... \ 1]\zeta^{-1}P_D(A) \tag{5}$$

Observability is a property of dynamic systems that indicates whether it is possible to infer the value of internal state variables from measurements or output variables, and is given by the equation (6):

$$O = \begin{bmatrix} C \\ C*A \\ C*A^2 \\ . \\ . \\ . \\ C*A^{N-1} \end{bmatrix} \tag{6}$$

$$rank(O) \geq N \tag{7}$$

With the above equations it can be calculated if the system is observable, and if this is fulfilled, the observer's gains (L) can be computed by (8).

$$L = PD_O(A) * O^{-1} * \begin{bmatrix} 0 \\ 0 \\ . \\ . \\ . \\ 1 \end{bmatrix} \tag{8}$$

The equations that represent the estimation of state variables, are defined as follows

$$\dot{\tilde{x}}(t) = A\tilde{x}(t) + Bu(t) + L(y(t) - \tilde{y}(t)) \tag{9}$$

$$\tilde{y}(t) = C\tilde{x}(t) + Du(t) \tag{10}$$

In order to obtain the reference tracking a constant matrix K_r is computed in (11).

$$K_r = \frac{1}{(C - DK)(-A + BK)^{-1}B + D} \tag{11}$$

By considering the aforementioned equations, a block diagram representing the entire control system with tracking constants, control constants, and state variable estimator can be constructed, as shown in Fig. 1.

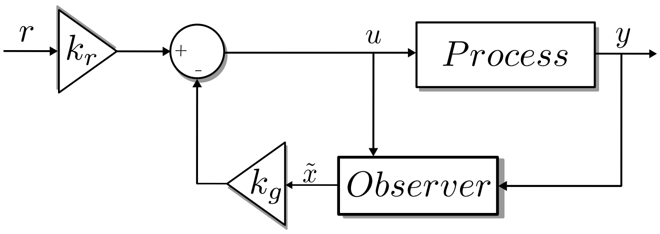

Fig. 1. Block diagram with state variables

In a discrete-time system, time is measured in discrete steps, which means that the state of the system is only updated at specific points in time and requires digital/analog converters as shown in the Fig. 2.

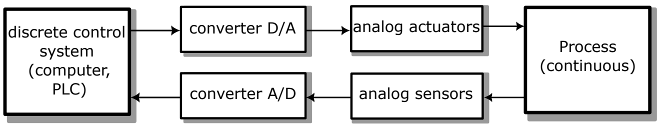

Fig. 2. Block diagram for discrete control

In order to obtain a discrete approximation of the continuous systems, the Zero Order Holder method, which is constructed by taking data and holding the continuous signal at a constant value until new data acquisition in time, is implemented as follows:

$$F = e^{Ah} = I + Ah + A^2\frac{h^2}{2!} + A^3\frac{h^3}{3!} + ... \quad (12)$$

$$G = \int_0^h e^{As}\, dsB \quad (13)$$

$$= (Ih + A\frac{h^2}{2!} + A^2\frac{h^3}{3!} + A^3\frac{h^4}{4!} + ...)B \quad (14)$$

Equations (12) and (13) show the calculation to discretize the matrices A and $B$of the continuous model in state space. As a result, the discrete equation in state space is shown as follows

$$x(t_{k+1}) = Fx(t_k) + Gu(t_k) \quad (15)$$

$$y(t_k) = Cx(t_k) + Du(t_k) \quad (16)$$

B. Arduino based HIL structure

Two DUE Arduino are used, as shown in Fig. 3, to obtain a HIL structure for simulation of dynamical systems. In this structure, one Arduino simulates the controller and the other Arduino simulates the plant.

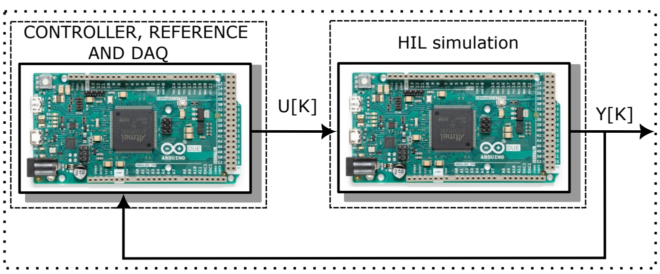

Fig. 3. Real-time simulation and control

C. Dynamic systems

Three systems are considered for simulation of the proposed Arduino based HIL structure. An RLC circuit, a twin rotor MIMO system, and a microgrid.

1) RLC circuit: Consider an RLC circuit where the input is the system voltage and the output is the current through the inductance, as shown in Fig. 4.

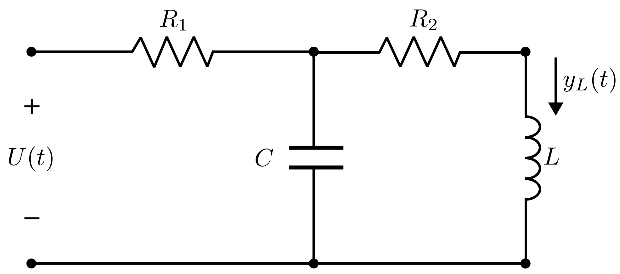

Fig. 4. RLC circuit

By solving the circuit and using state variables, the following state space model is obtained:

$$\begin{bmatrix}\dot{x}_1(t)\\ \dot{x}_2(t)\end{bmatrix} = \begin{bmatrix}\frac{-1}{R_1C} & \frac{-1}{C}\\ \frac{1}{L} & \frac{-R_2}{L}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix} + \begin{bmatrix}\frac{1}{R1*C}\\ 0\end{bmatrix}u(t) \quad (17)$$

And the output of the system is as follows:

$$y_L(t) = \begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix} \quad (18)$$

The following I+PD control structure shown in block diagrams in the Fig. 5 is used.

The controller constants are defined as follows:

- $K_i = 111.413$
- $K_d = 11.9465$
- $K_p = 48.6063$

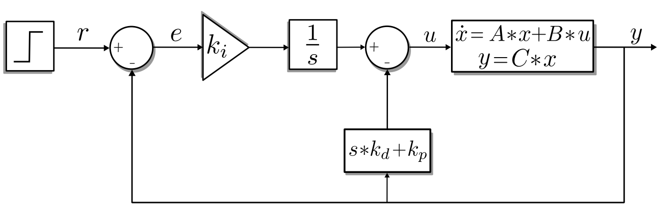

Fig. 5. I+PD controller block diagrams

2) Twin Rotor MIMO System: The twin rotor MIMO system is a multivariable nonlinear system of two inputs and two outputs of sixth order. A linearized state space model can be obtained as follows:

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -4.7059 & 0.0882 & 0 & 0 & 1.3588 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -5 & 1.617 & 4.5 \\ 0 & 0 & 0 & 0 & -0.9091 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} x(t) + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0.8 \end{bmatrix} u(t) \tag{19}$$

where the output of the multivariable system is defined by:

$$y(t) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} x(t) \tag{20}$$

Matlab is used to discretize the system using the ZOH discretization method with a sample time of $h = 0.1$ seconds. Also the calculation of the control constants and their respective state observer are computed based on the discrete matrices. The discrete matrices are defined as follows:

$$F = \begin{bmatrix} 0.9766 & 0.0988 & 0 & 0 & 0.0065 & 0 \\ -0.4649 & 0.9679 & 0 & 0 & 0.1283 & 0 \\ 0 & 0 & 1 & 0.0787 & 0.0067 & 0.0185 \\ 0 & 0 & 0 & 0.6065 & 0.1212 & 0.3356 \\ 0 & 0 & 0 & 0 & 0.9131 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.9048 \end{bmatrix}$$
$$G = \begin{bmatrix} 0.0002 & 0 \\ 0.0065 & 0 \\ 0.0002 & 0.0005 \\ 0.0067 & 0.0148 \\ 0.0956 & 0 \\ 0 & 0.0761 \end{bmatrix} \tag{21}$$

The feedback constants for the multivariable system of (22) and the observer constants of (23), as well as the tracking constants of (24) are defined as

$$K_d^T = \begin{bmatrix} 0.3795 & 55.0147 \\ 28.9847 & 3.5685 \\ 10.0461 & 46.4597 \\ 1.7884 & 9.2761 \\ 10.0079 & 1.3837 \\ 0.8055 & 11.4624 \end{bmatrix} \tag{22}$$

$$L_d = \begin{bmatrix} 1.2839 & 0.0121 \\ 4.3382 & 0.1141 \\ 0.0009 & 1.1457 \\ 0.0218 & 2.9781 \\ 4.1533 & 0.2460 \\ -1.4425 & 2.6427 \end{bmatrix} \tag{23}$$

$$K_{rd} = \begin{bmatrix} 37.1858 & 10.0461 \\ 43.9867 & 46.4597 \end{bmatrix} \tag{24}$$

The block diagram describing the twin rotor MIMO system is presented in Fig. II-C2.

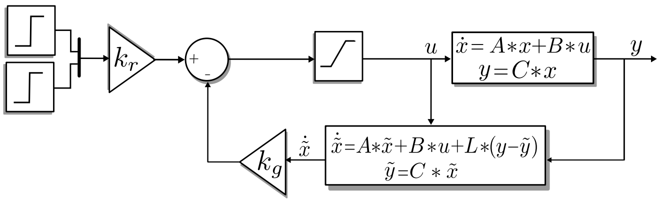

Fig. 6. Block diagram of Twin Rotor system

3) Microgrid: Finally, a microgrid of the Fig. 7 is identified using a Kalman filter to reduce the number of state variables. In this case, the number of state variables is seven.

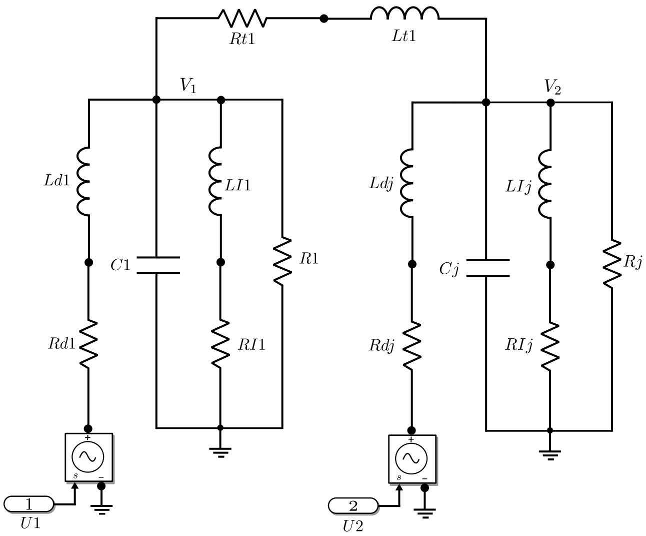

Fig. 7. Microgrid dynamic system.

The same procedure is performed to obtain the discrete matrices of the microgrid shown in Fig. 7 using a sampling time of $h = 0.01$.

$$F = \begin{bmatrix} 0.9918 & -0.0147 & 0.2276 & 0.0136 & -0.0091 & -0.0129 & 0.215 \\ -0.0002 & 0.9704 & 0.0163 & -0.233 & -0.0094 & 0.0265 & -0.2632 \\ -0.0002 & 0.004 & 0.972 & 0.0482 & 0.4857 & 0.0805 & 0.1051 \\ 0.00004 & 0.003 & 0.0256 & 0.9315 & -0.0852 & 0.484 & 0.1326 \\ 0.0001 & 0.0003 & -0.0023 & -0.007 & 0.9052 & -0.0712 & 0.3106 \\ 0.00002 & -0.0004 & -0.0018 & 0.0016 & -0.0332 & 0.9275 & 0.6954 \end{bmatrix} \tag{25}$$

$$G = \begin{bmatrix} -0.0155 & -0.0151 \\ -0.0134 & 0.0145 \\ 0.0079 & -0.0049 \\ 0.0069 & -0.0075 \\ 0.0007 & 0.0023 \\ -0.0002 & 0.0016 \\ 0 & 0 \end{bmatrix} \tag{26}$$

$$C = \begin{bmatrix} -0.1953 & -0.235 & 0.3369 & -0.3564 & -0.4027 & 0.231 & -0.0434 \\ -0.1909 & 0.2046 & 0.2839 & 0.3129 & -0.3199 & -0.4367 & 0.4149 \end{bmatrix} \tag{27}$$

The control constants of (28), the observer gain of (29), and the tracking gain of (30) are calculated as follows:

$$K_d^T = \begin{bmatrix} -0.5489 & -0.528 \\ -0.0908 & 0.4725 \\ -2.1635 & -2.1380 \\ -0.2956 & -1.6973 \\ -8.3284 & -5.4943 \\ 2.3871 & -4.9667 \\ 492.5805 & 181.8763 \end{bmatrix} \tag{28}$$

$$L_d = \begin{bmatrix} -4.8643 & -19.9531 \\ -7.1586 & 21.916 \\ -1.696 & -10.4305 \\ 3.6686 & -16.9732 \\ -0.5459 & 0.7295 \\ 0.8389 & -4.5427 \\ 0.0754 & -0.6938 \end{bmatrix} \tag{29}$$

$$K_{rd} = \begin{bmatrix} 1305.3 & -5.6 \\ -5.7 & 1305.6 \end{bmatrix} \tag{30}$$

The above matrices are used to simulate in real-time using Arduino and the HIL proposed structure. An additionalsimulation under Matlab-Simulink environment is used to compare these responses.

III. Results

In order to evaluate the performance of the proposed approach over the aforementioned systems, a simulation by using Matlab-Simulink and the Arduino-based HIL structure is performed.

For the circuit of the Fig. 4, the simulation is performed in Matlab with its respective controller proposed in the Fig. 5 and a similar response is expected in the real implementation with the Arduino-based HIL structure.

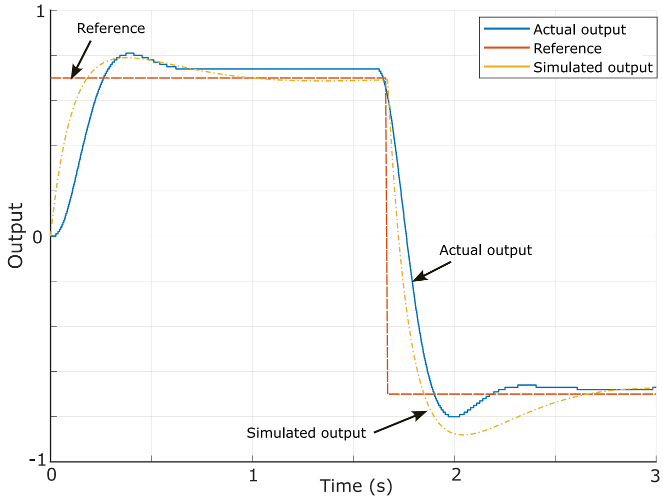

Fig. 8. Circuit RLC

In Fig. 8 is shown that the real-time graph has a similar response to the one simulated in Matlab, but with an additional delay. However, it can be assured that the system reaches the reference in a similar time.

In Fig. 9 is shown the graph of the twin-rotor MIMO system for the first output of the system compared to the first reference.

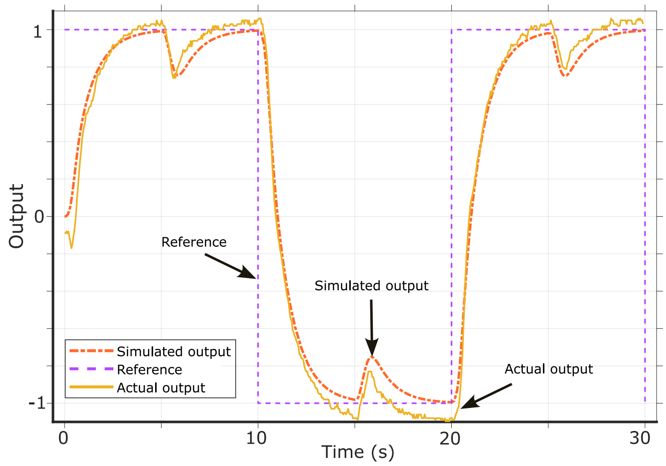

Fig. 9. First output of the twin rotor MIMO system

In Fig. 9 is shown the comparison of a system simulated in real-time compared to a software simulation by using Simulink. A detailed view of the comparison of Fig. 9 is shown in Fig. 10.

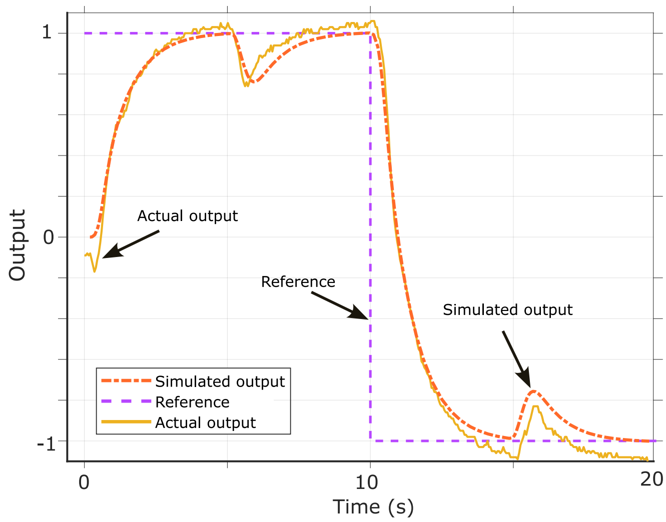

Fig. 10. Detailed view of the first output of the twin rotor MIMO system

In Fig. 11 is shown the second input for the twin rotor MIMO system.

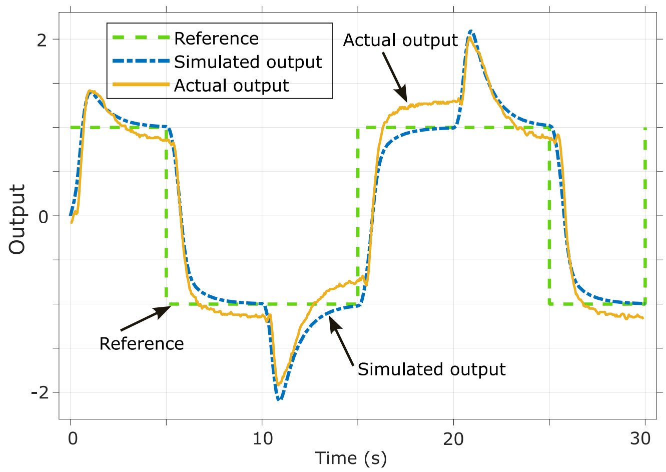

Fig. 11. Second output of the twin rotor MIMO system

In Fig. 11 can be observed the reference tracking performance for the second output of the twin rotor MIMO system. It is worth noting that a steady state error is shown for the reference tracking due to an inherent internal coupling between the two outputs of the system. That behaviour can be also considered as an external disturbance. A detailed view of the comparison of Fig. 11 is shown in Fig. 12.

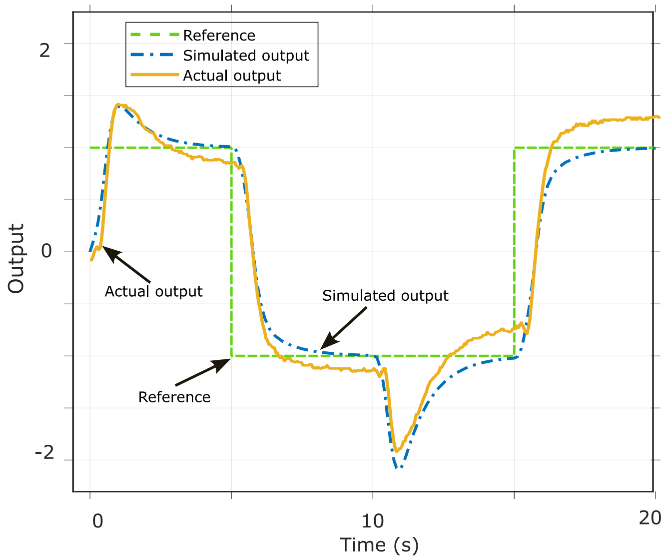

Fig. 12. Detailed view of the second output of the twin rotor MIMO system

In the Fig. 13 is shown the comparison of the first microgrid voltage output simulated in real-time compared to a software simulation by using Simulink.

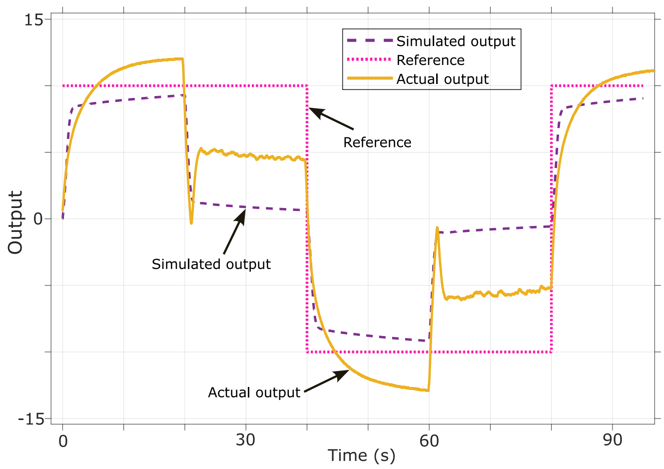

Fig. 13. First microgrid voltage output

From Fig. 13 it can be concluded that the proposed controller needs an integral action to reduce the steady state error.

In the Fig. 14 is shown the comparison of the second microgrid voltage output simulated in real-time compared to a software simulation by using Simulink.

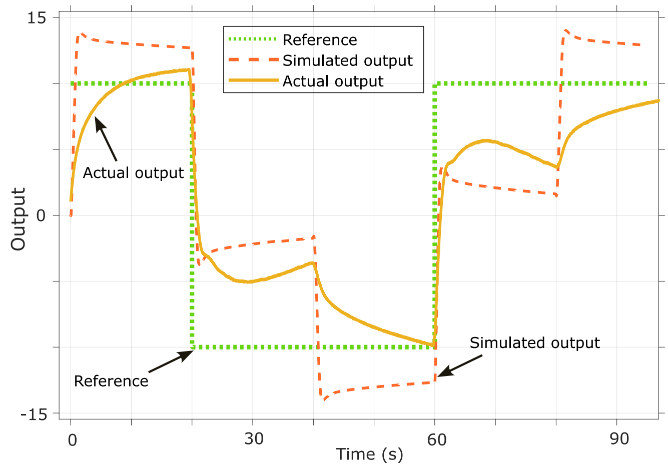

Fig. 14. Second microgrid voltage output

From Fig. 14 and Fig. 13 can be concluded that the microgrid system has also an inherent internal coupling and therefore the system requires a multivariable coupled controller.

The Fig. 15 shows the real implementation of the HIL structure by using two Arduinos DUE. The Arduino DUE has two analog outputs that are used to interconnect the controller and the plant and that are also used visualize the results by using an oscilloscope. That connection is used for each of the test systems.

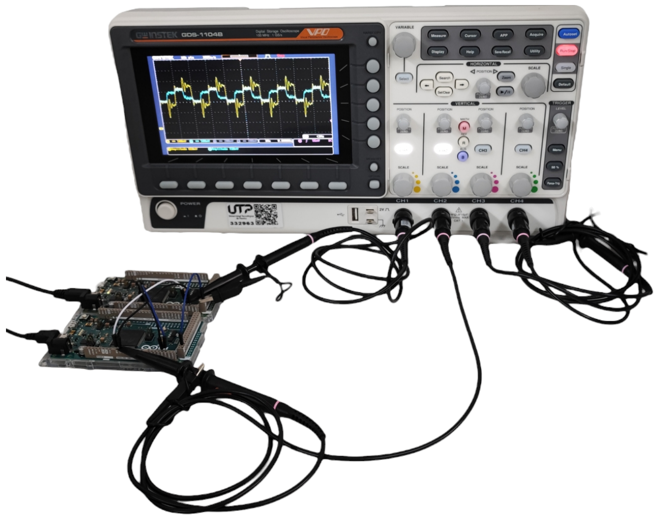

Fig. 15. HIL interconnection structure by using two Arduinos DUE

IV. Conclusions

A low-cost methodology consisting of two Arduinos to perform real-time controllers and simulations of any plant using HIL is presented. This makes it possible to have decentralized control with any multivariable dynamic system. It also achieved the interconnection between 2 Arduinos. It also compared the responses obtained in real time and those simulated by a computer.

Three systems are validated with their respective controllers, where it can be concluded that the response of the systems will depend a lot on the computation time required by the Arduino. The larger the system, the more time it will take to perform all operations so that that time will be closely related to the sampling time of each plant and controller. In order to capture, analyze, and validate the data, a Python program is developed. As a result, a detailed analysis of each controller's performance is obtained.

For future work, it is proposed to make controllers using advanced and robust techniques so that there is not so much error between the simulated signals in real-time compared to computer simulation, such as the implementation of faster microprocessors and more computational time to perform operations that require each system as increasing the number of inputs and outputs of the systems.

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