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A Virtual Environment for Remote Testing of Complex Systems

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***Abstract*—Complex systems, realized by integration of several components or subsystems, pose specific problems to simulation environments. It is, in fact, desirable to simulate the complex system altogether, and not component by component, since the operation of the single part depends on the surrounding system and an early verification can prevent damages and save time for modifications. The availability of detailed and validated models of the single parts is therefore critical. This task may be difficult to achieve. In fact, in industrial applications, where a system can be a mix of different devices produced by different manufacturers, the physical device may not be accessible to the modeler for proprietary or safety concerns. Starting from this point, the idea of creating a virtual environment able to test the real single component remotely, employing simulators with remote signal processing capability, has been considered. In this paper a methodology for remote model validation is presented. The effectiveness of the approach is experimentally verified locally and remotely. For the remote testing, in particular, the physical device under test is located at the Politecnico di Milano, Italy, and the Virtual Test Bed model is located at the University of South Carolina.**

***Index Terms*—Cosimulation, distributed computing, electric variables measurement, model security, remote testing.**

I. INTRODUCTION

COMPLEX systems, realized by integration of several components or subsystems, each of which can also be represented as a complex system, are increasingly employed in industrial applications, health-care systems, environmental sensing and monitoring, and military systems. The complexity of these systems leads to difficulties in simulation and testing. Exhaustive testing of such systems cannot be done by testing each component or subsystem independently, since even when all of them meet their own specifications, unpredictable interference and/or malfunctions may appear when the whole system is assembled. If these malfunctions could be detected with preliminary tests, the economic benefits would be extremely great.

Moreover, several applications exist where the whole system is realized with components produced by different manufacturers, often in competition with each other. Most of the technical information that each manufacturer makes available to the final customer is strictly confidential, and is not supposed to be forwarded to other manufacturers, making it difficult to perform exhaustive tests. When military systems are involved, this is reinforced by security concerns.

The availability of a virtual environment (VE) that would allow testing the single components as if they were already part of the whole system, before the system is actually assembled, appears to be the best solution to the problems sketched above. If the VE featured the capability of processing remote signals, tests could be performed at the customer's site, leaving the device under test (DUT) at the manufacturer's site. This would result in a dramatic reduction of time and cost of moving the DUT from the manufacturer's to the customer's site for testing, and back to the manufacturer's site for modifications, if needed. Moreover, no confidential information about the whole system would need to be passed on to the manufacturer.

This paper presents an application based on the partnership between a virtual instrument (VI) with remote signal processing capabilities and a virtual test bed (VTB) that realizes the VE. The described method allows model validation, use of validated models for monitoring and diagnostics, and incremental complex system design. This paper shows the application of the VE to three scenarios: remote model validation of a filter and of a single phase transformer, and design verification of a fuel cell supplying a dc motor drive.

II. VIRTUAL TEST BED AND THE LABVIEW ACQUISITION PLATFORM

The simulation of complex systems where many components of different natures interact presents peculiar challenges. Different users might analyze an individual system focusing on different aspects of the system performance and having a different metric for what is important. The complexity of the system may bridge several areas of technical expertise, and users in each of those technical areas traditionally work with their own set of design and simulation tools.

Suppliers of a particular subsystem may have already invested significant efforts in the creation of a simulation model for that subsystem, which encapsulates their in-depth knowledge of the system. Exporting the model to the simulator of choice for the overall system is difficult and time-consuming and results in a duplication of efforts.

Moreover, some parts of the system may be already available while other parts are still being designed. To the extent possible, one may wish to substitute real components for models every time a new component becomes available. Such an approach would keep the design/simulation "alive," promote iteration, and allow an opportunity to validate models and to de-

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tect, at the earliest possible time, potentially complicating nuances that were not originally accounted for in the component models. The cost of this approach is that it would require a sophisticated capability for working with diverse modeling languages and with hardware in the loop [1].

All of these considerations suggest the desirability of a new high-level interface that allows many types of users to be comfortable with the virtual prototyping tool. An attempt to develop such a tool has been under way at the University of South Carolina (USC) for several years now under the program name Virtual Test Bed [2], [3].

The VTB approach solves the traditional dichotomy in modeling that universally plagues designers, allowing them now to use a proper instrument for each part of the system design problem. In contrast, classical simulators, where a single specification language is available to the users, greatly limit the analysis of complex systems. The VTB environment addresses these challenges by choosing to support.

- *Multiformalism:* different languages can be used to build models of the different components of a system. This allows an individual to build models using the preferred language within his or her discipline (mechanical, electrical, chemical, etc.).
- *Cosimulation:* users can change the language and also use other solvers together with the main VTB solver. This means that any part can be solved with the most appropriate integration step and method without affecting the solution of the rest of the system.
- *High-level visualization:* visualization models of the system can be easily created and linked to live simulation data. Visualization helps the user to rapidly comprehend the system performance. Visual outputs include data-driven animation of the motion of solid objects, imposition onto solid objects of novel representations of abstract simulation data, or simply oscilloscope-like graphs. Furthermore, a high-level visualization better supports the interchange of information among the designers cooperating on the project.
- *Hardware in the simulation loop:* this is a rather new feature of the VTB environment.

The capability of VTB to integrate into its own simulation environment components modeled in different languages and environments has been extended to widely popular design tools, as extensively described in [4]–[6]. The newest extension is LabVIEW. This new cosimulation capability opens a whole new set of possibilities related to the pretesting of VIs and the use of the integrated environment for the training of the instrument itself, if needed, and of the operator. Moreover, real signals coming from the DUT can easily be acquired and processed by the VIs within the LabView environment [7]. The real measured data can hence be compared with those simulated in the VTB environment, thus allowing assessment of whether or not the DUT meets the design specifications. Conversely, the real measured data can be supplied to the other blocks of the VTB simulator for analysis of how the other components in the system react to the presence of a real component.

Moreover, LabVIEW adds a new important feature to VTB: the capability of including also remote testing facilities in the Virtual Test Bed, due to extremely easy way it can handle remote signal acquisition resources and interconnect to remote devices through the Internet.

It is known that the use of the Internet as a flexible and powerful interconnection media has been already exploited for the implementation of distributed measurement systems. Several applications have been proposed in the literature [9]–[17], mainly for educational purposes, where the different units in the distributed systems were connected through a local-area network or also a wide-area network. However, to the author's knowledge, none of the proposed solutions has implemented a true virtual environment, with hardware-in-the-loop capabilities, such as shown in [8] and extended in this paper.

III. VIRTUAL INSTRUMENT AND VIRTUAL TEST BED PARTNERSHIP

The process of interaction between VTB and LabView is based on the dynamic link library (DLL). The LabView environment is able to export any VI project in the format of a DLL. The DLL is also the basis for library management in the VTB software. Thanks to the definition of a new model class, the VTB software is now able to recognize, load, and execute LabView DLLs.

To verify the effectiveness of the implemented interface, let us focus on a very simple example. The case study features VTB providing parameters to LabView that operates like a signal generator and supplies the desired signal to VTB. The VTB schematic in Fig. 1 shows the LabView VI wrapped in a VTB block, the VTB blocks providing parameters to the LabView block, and the scope allowing the visualization of the signal created by LabVIew and passed on to VTB. The capture in the upper left corner represents the LabView VI schematic. This has been compiled and then imported into VTB, as shown in the main central picture. Activating the VTB simulation, LabView generates the desired sinusoidal signal as reported in the upper right corner. With this procedure the VI designed to create the desired signal was tested. This example shows a trivial VI but the procedure can be applied to any level of complexity allowing the virtual testing of any VI developed within LabView. To perform the connection between the two environments, a set of options were considered. The two most significant cases are described in the following.

1) The whole process is performed by using virtual data. The LabView environment can have input and output data exchange with VTB.
2) LabView generates test cases for the VE after acquiring data from a real plant. This process can be performed sending one sample per simulation cycle or it can be based on a buffer of acquired data. The second case easily allows remote execution without any concern for the delay introduced by the network connection, as long as hard real-time operations are not necessary.

The availability of the described environment allows the execution of critical activities that are here summarized.

- Validation of a VTB model: by acquiring system inputs and outputs from the real device it is possible to validate the simulation model available in the VTB environment. The procedure is performed imposing to the simu-

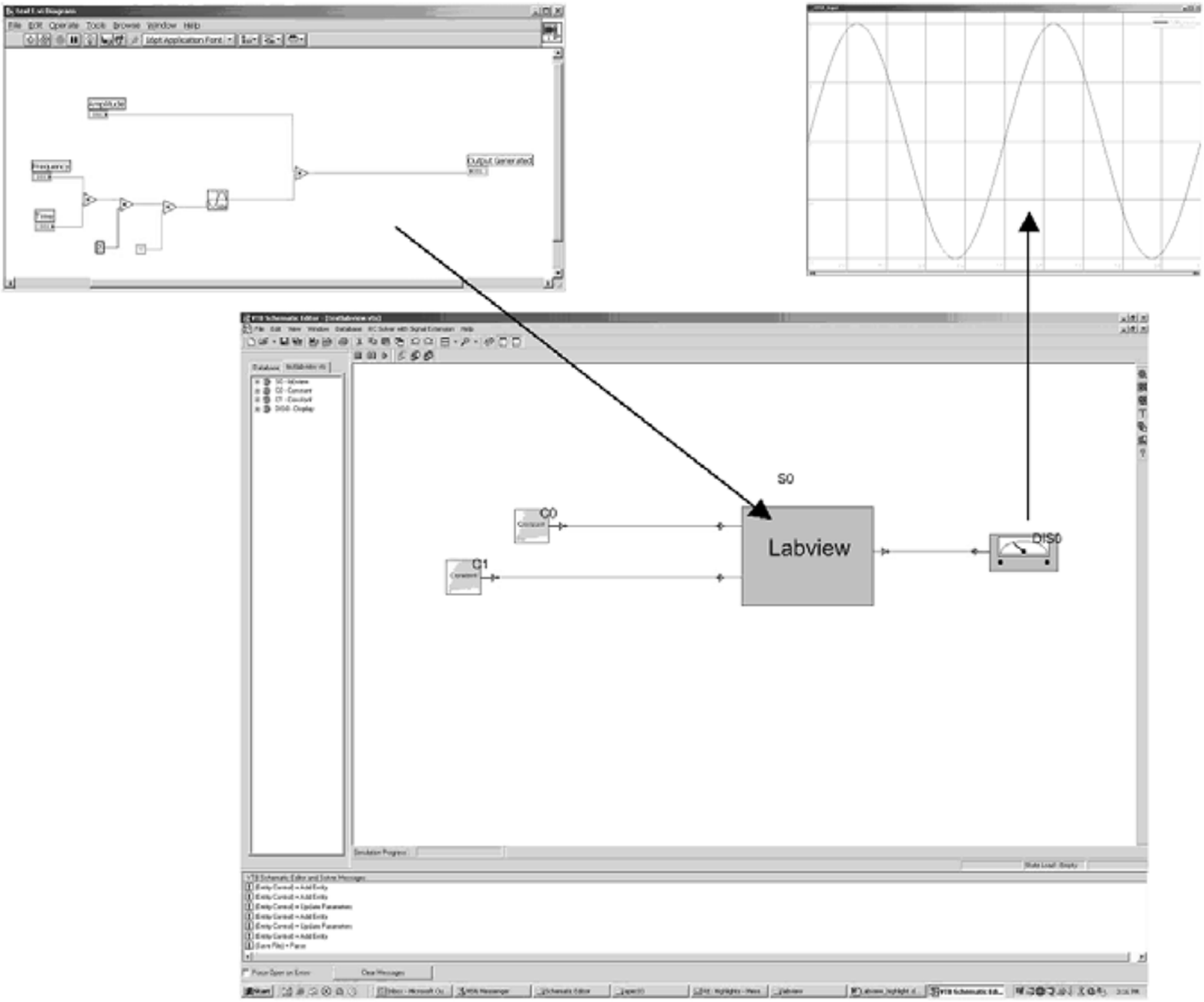


Fig. 1. VTB and LabView cosimulating.

lated system the same input the real system experiences and comparing real and simulated outputs

- Monitoring of a system whose validated model is available: once the model has been validated it is possible to use the same procedure described above to periodically compare real data and simulated data. Any deviation from the standard behavior can be easily identified by continuously comparing the validated model outputs with the acquired data.
- Troubleshooting of a plant: once a validated model is available and the deviation from the standard behavior has been determined, it is possible to use the simulated system to determine the cause for the deviation itself.
- Insertion of new equipment in a large plant: if new equipment has to be inserted into a complex plant, it is possible to use real data from the plant to test the sensitivity of the new equipment to any kind of disturbance present in the system.

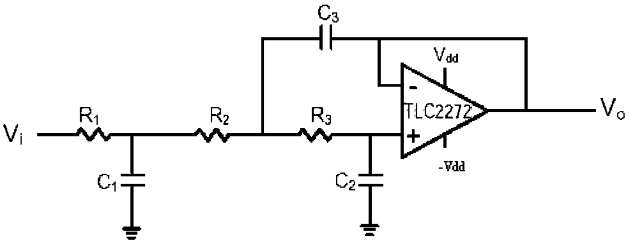
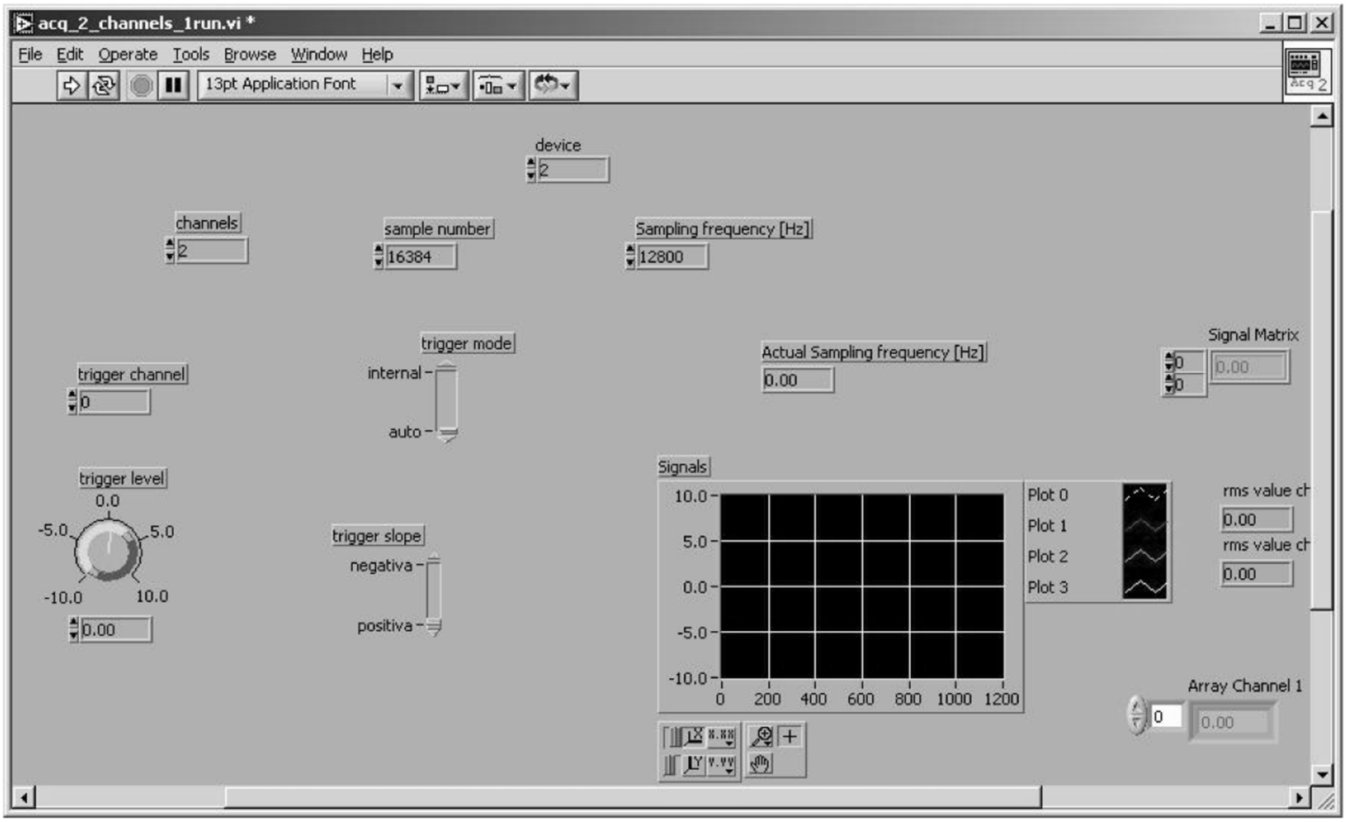


Fig. 2. The filter under test.

TABLE I
VALUES ADOPTED FOR THE ELEMENTS OF THE CIRCUIT IN FIG. 2

Description	Value
R1	160 KΩ
R2	240 KΩ
R3	750 KΩ
C1	0.1 μF
C2	0.01 μF
C3	0.047 μF

In the following, two simple examples of application of the proposed methodology for model validation are described. In the first case the equipment under test was located in the same building as the simulation platform, while in the second case the equipment was located in Italy and the simulation platform was located in the United States.



device 2

channels 2

sample number 16384

Sampling frequency [Hz] 12800

Actual Sampling frequency [Hz] 0.00

Signal Matrix 0 0 0.00

trigger channel 0

trigger level 0.0 0.00

rms value ch 0.00

rms value ch 0.00

Array Channel 1 0 0.00

Fig. 3. The VI adopted to handle the data sampling.

IV. EXAMPLE OF APPLICATION: ANALOG FILTER MODEL VALIDATION

In this first example, a simple third-order active filter is considered, as reported in Fig. 2. The values adopted for the circuit elements are reported in Table I. The filter has been connected to an external signal generator and the input and output voltages have been connected to a data acquisition board equipped with eight input channels, ±10 V range, with simultaneous sampling up to 500 kHz sampling rate on a single channel. This board is handled through the LabView VI reported in Fig. 3.

This VI is able to capture a buffer of data for the two channels, acquiring the signals with a predefined sampling frequency. All the acquisition parameters can be defined through the VI panel.

By exporting the VI to a DLL it is possible to create a suitable function that makes the buffer available for every instance of a function call. The VTB block designed to interface this kind of LabView function is able to collect the buffer and to release the samples to the virtual environment, emulating the correct time evolution.

The target of this experiment is the comparison of the real filter output with the output simulated by VTB using the theoretical transfer function of the filter. Fig. 4 illustrates the VTB setup: the LabView block is parameterized to load the specific DLL created by the VI in Fig. 3. By running the simulation, the LabView-VTB block acquires the measured input and output of the real system and creates two streams of signals available to the rest of the simulated environment: channel 1, representing the real input of the filter, is used as the input for the model, while channel 2, representing the output of the real filter, can be compared with the output of the simulated filter. Applying as input the signal reported in Fig. 5, the results of Fig. 6 have been obtained. In order to create a measure of the quality of the simulation, the following index has been defined:

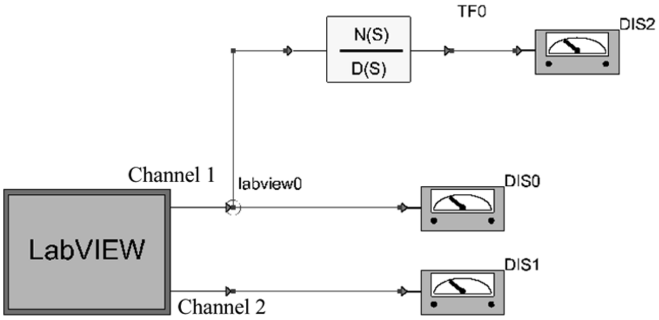


Fig. 4. The VTB schematic for the filter example.

$$e = \frac{\sqrt{\sum_k (vm_k - vs_k)^2}}{\sqrt{\sum_k vm_k^2}} 100$$

where

vm_k generic sample of the measured quantity;
vs_k generic sample of the simulated quantity.

This index is a sort of relative rms deviation, over one period of the considered signal, between the measured quantity and the simulated one. In this specific example a value of 4.88% has

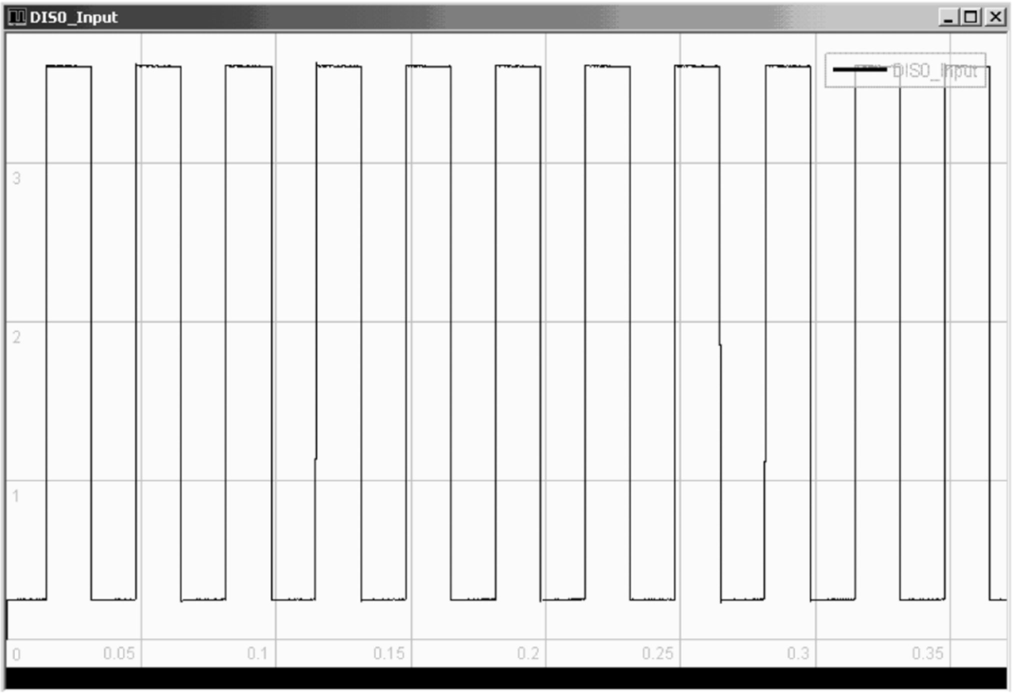


Fig. 5. The acquired input signal (x-axis in seconds and y-axis in volts).

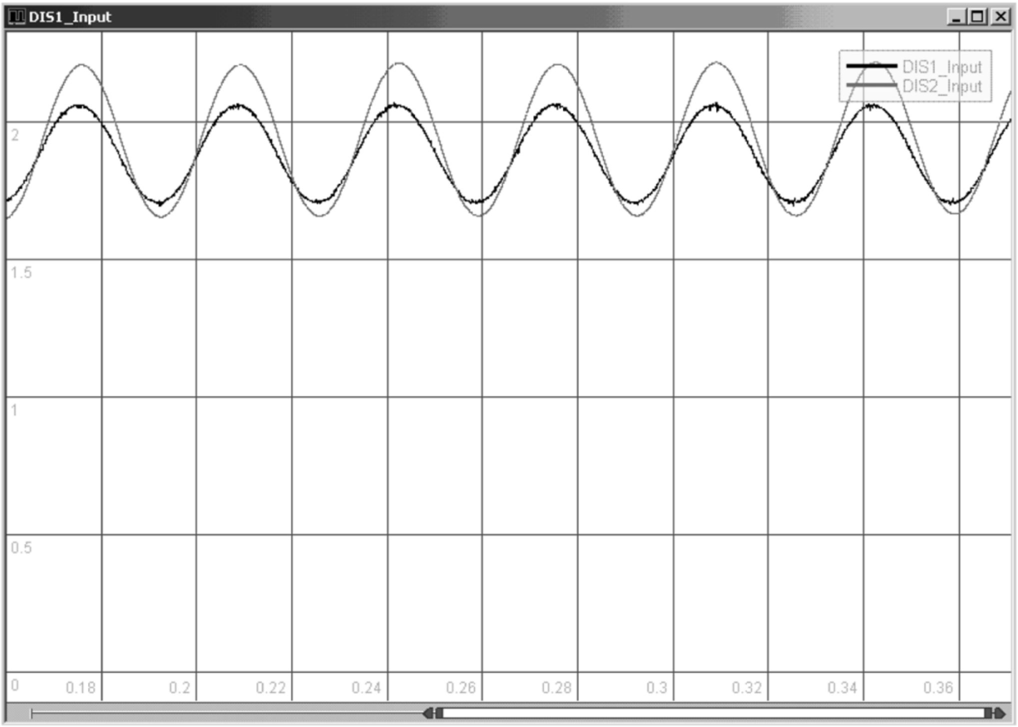


Fig. 6. Comparison between theoretical and real output signals for the filter case.

been calculated. Such a result can be considered a starting point to evaluate the quality of the model and, if desired, as a reference to improve the quality of the model. In this case, for example, it has been estimated that part of the error was related to the nonlinearity of the operational amplifier, working too close to the saturation limit (the power supply was working at ±5 V). To verify this assumption, the experimental comparison has been repeated with an input signal with a lower amplitude. The results are reported in Fig. 7 and show an overall improved matching of measured and simulated output.

Evaluating the quality index for this second experiment, a value of 2.23% has been obtained, showing an increment in the simulation accuracy of about 50%. Further improvement could be easily obtained and verified by inserting the correct values for the resistance and capacitance instead of the nominal values given by the manufacturer.

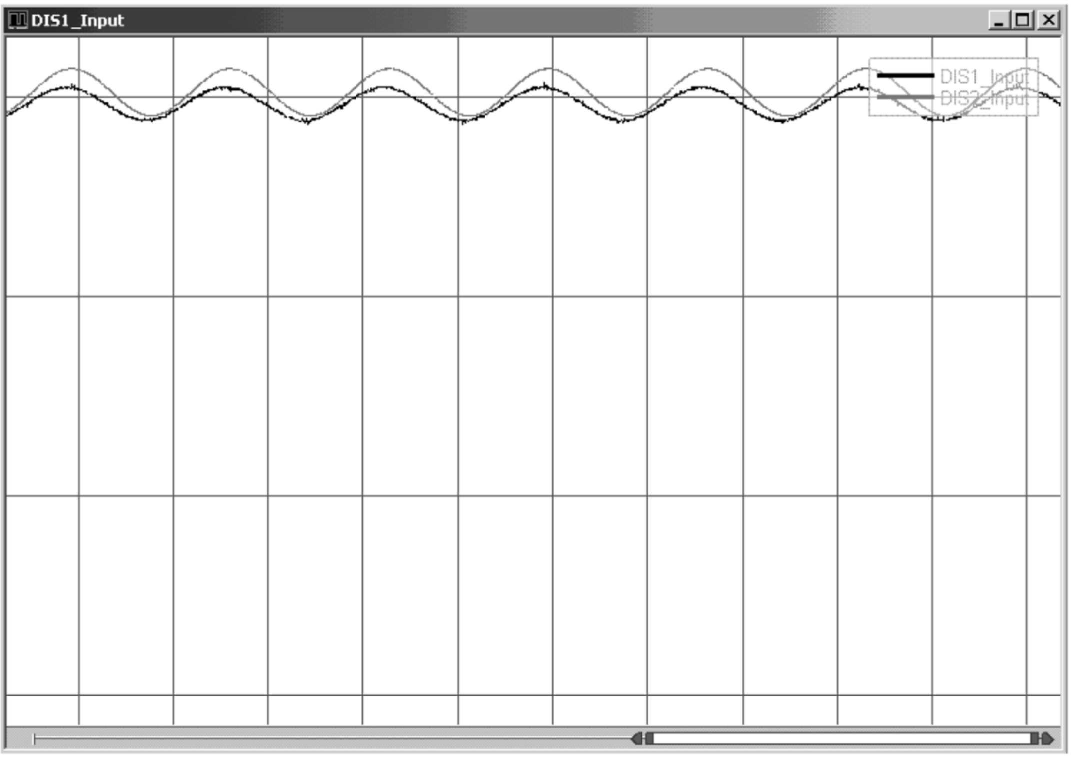


Fig. 7. A second experiment with the same filter model and input with smaller amplitude.

V. EXAMPLE OF APPLICATION: A TRANSFORMER MODEL

The aim of the second experiment is to prove the "hardware in the loop" structure; this structure allows to verify the capability of the VE to validate a model and perform remote testing at the same time. For this reason the experiment has been conducted adopting, as the test model, a transformer located in Italy, while the acquisition process for the simulation was performed in the United States. Since the aim of this experiment was the structure validation, and not the transformer test, the transformer itself has been supplied with a voltage much lower than its rated one, in order to avoid the use of voltage and current transducers in the test equipment.

The VI was executed within the VTB environment at the University of South Carolina and accessed, through an Internet connection, an analog-to-digital conversion acquisition board (ADC). The ADC was located in Milan, Italy. The connection was developed using the LabView Remote Device Access (RDA server); this protocol allows the control, as a shared resource, of an ADC device, plugged into a computer located on an Internet node.

The board adopted for the data acquisition features the same performance as the one used for the tests reported in Section IV, so the same VI as that shown in Fig. 3 could be used.

The transformer under test is a single-phase transformer, with 100 VA rated power and 210 V/18 V rated transformer ratio. In order to avoid the use of voltage transducers, the transformer has been fed with a 6.72 V rms sinusoidal signal. The ADC board channel dedicated to the acquisition of the transformer secondary voltage was set to a gain value of ten.

The VTB model has been obtained by combining an ideal transformer model and two suitable inductors to represent leakage and magnetization effects.

The VTB schematic is reported in Fig. 8. The two gain blocks connected to the LabView channels take into account the channel gains and adapt the signals to the proper voltage levels.

One channel is connected to the circuit simulation model where a signal-controlled voltage source feeds the transformer model with the same input signal as the one applied to the real transformer. Actual and simulation outputs are available within VTB and can be compared.

In this case the input signal is a sinusoidal voltage that is applied to the system working at no-load conditions. The time evolution is documented in Fig. 9. As reported in Fig. 10, the correspondence between simulated and real data is extremely close. Therefore, within certain constraints, the model could be applied to monitor the system under different operating conditions, in order to identify a possible malfunctioning.

VI. EXAMPLE OF APPLICATION: DYNAMIC BEHAVIOR OF A FUEL CELL FED SYSTEM

The purpose of this example is to show an application of the proposed approach that can be used in two perspectives: model validation on one hand, design of complex systems on the other hand. The scenario of the experiment is the following: a dc motor drive with viscous friction load is operated through a buck converter and supplied by a fuel cell. The VTB schematic of the experimental setup is reported in Fig. 11.

As far as model validation is concerned, the purpose of the experiment is to verify the accuracy of the fuel cell model with respect to the physical device. During the experiment, the VTB model of the fuel cell will be tested against the real device, provided that the real system is working under the same conditions as the simulated one.

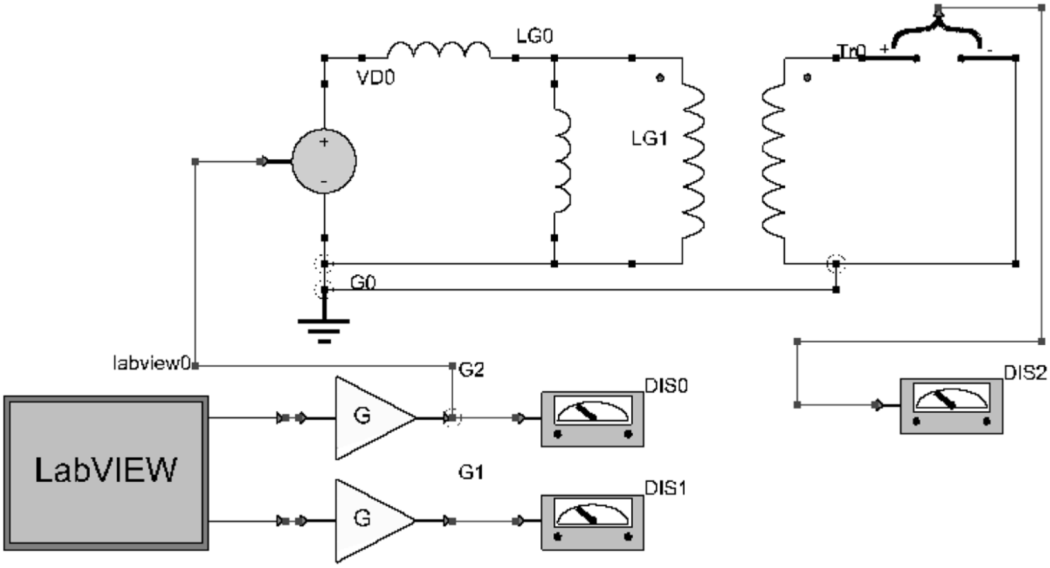


Fig. 8. The VTB schematic for the transformer example.

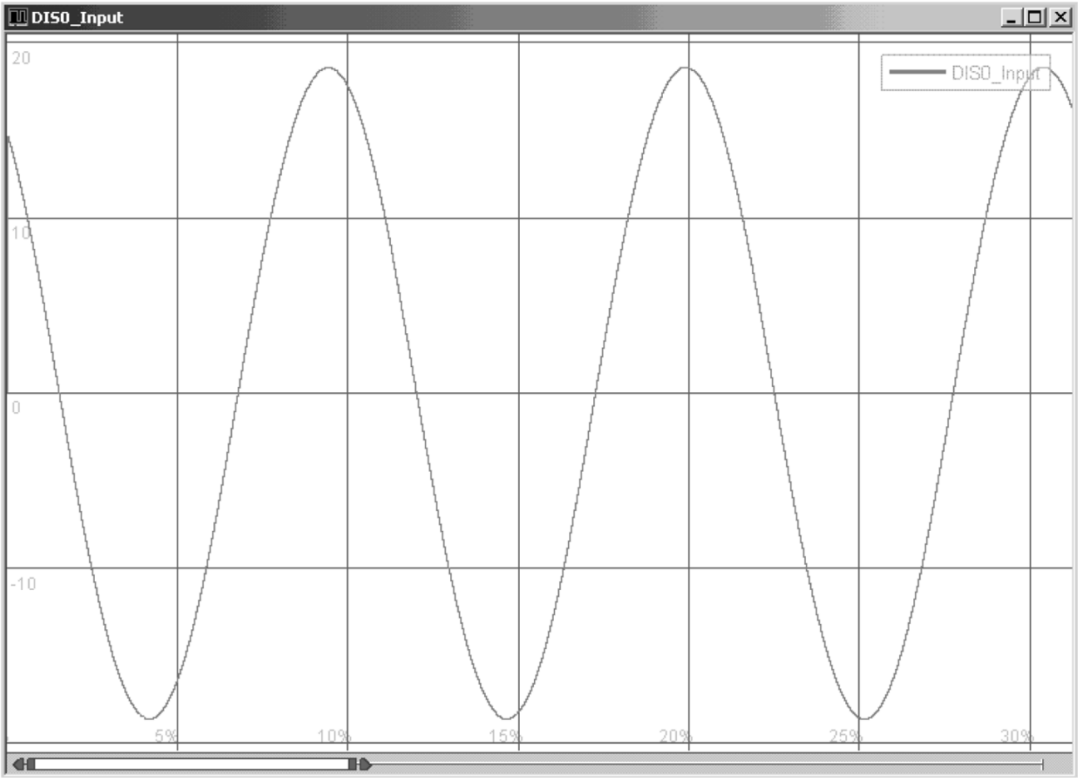


Fig. 9. The transformer input voltage (x-axis in percentage of saved data, y-axis in volts).

As far as concerns the design verification, running the experiment it is possible to evaluate if the fuel cell is able to match the power demand and dynamic. The availability of the proposed platform allows the designer to test the fuel cell dynamically even if the real final load is not available.

A programmable load is forced to operate dynamically emulating the power demand of the simulated load.

The designer can test the component (the fuel cell in this case) under many different loading scenarios without having the real loads available.

In this case for example, we analyze as load a dc motor fed by a power converter.

During the experiment the simulation of the fuel cell loaded with the buck converter and the dc motor drive runs together with the physical system where the fuel cell supplies a programmable load whose power demand replicates that of the buck converter and motor drive. In Fig. 12 the experimental setup is shown to clarify the connections between the physical and virtual system. This experimental setup allows design verification of the chosen fuel cell and, on the other hand, allows the

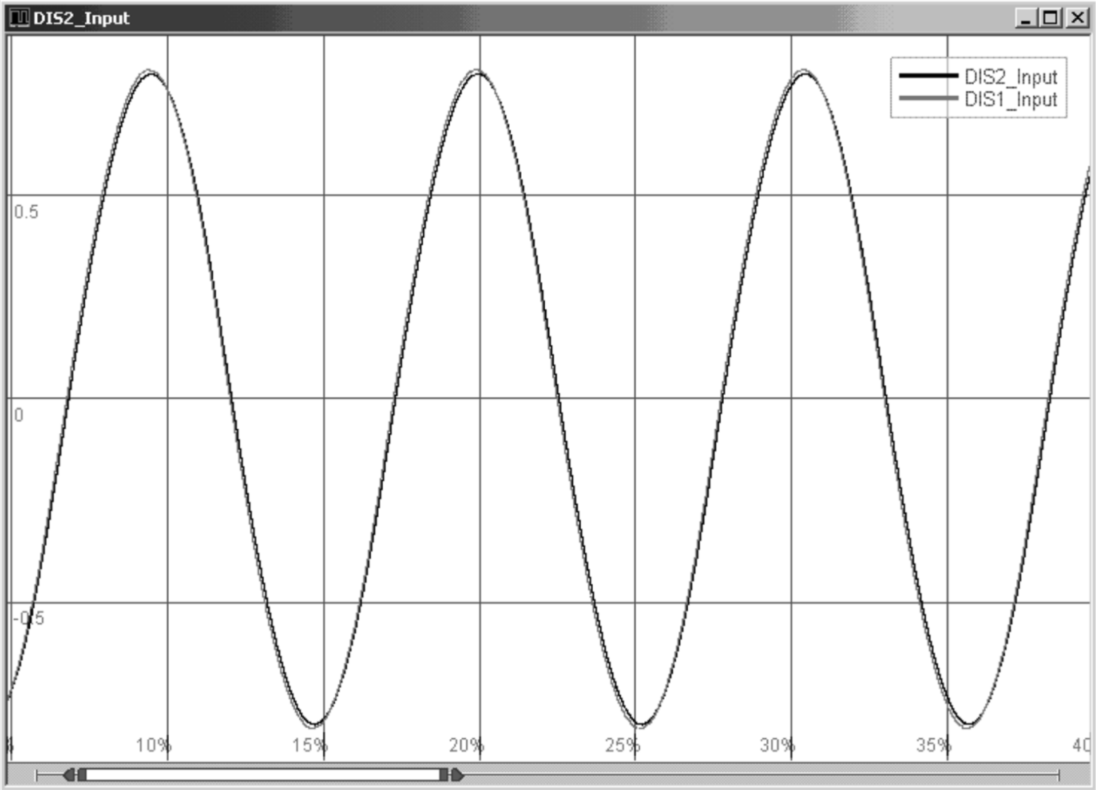


Fig. 10. Comparison between simulated and real secondary voltages for the transformer (x-axis in percentage of saved data, y- axis in volts).

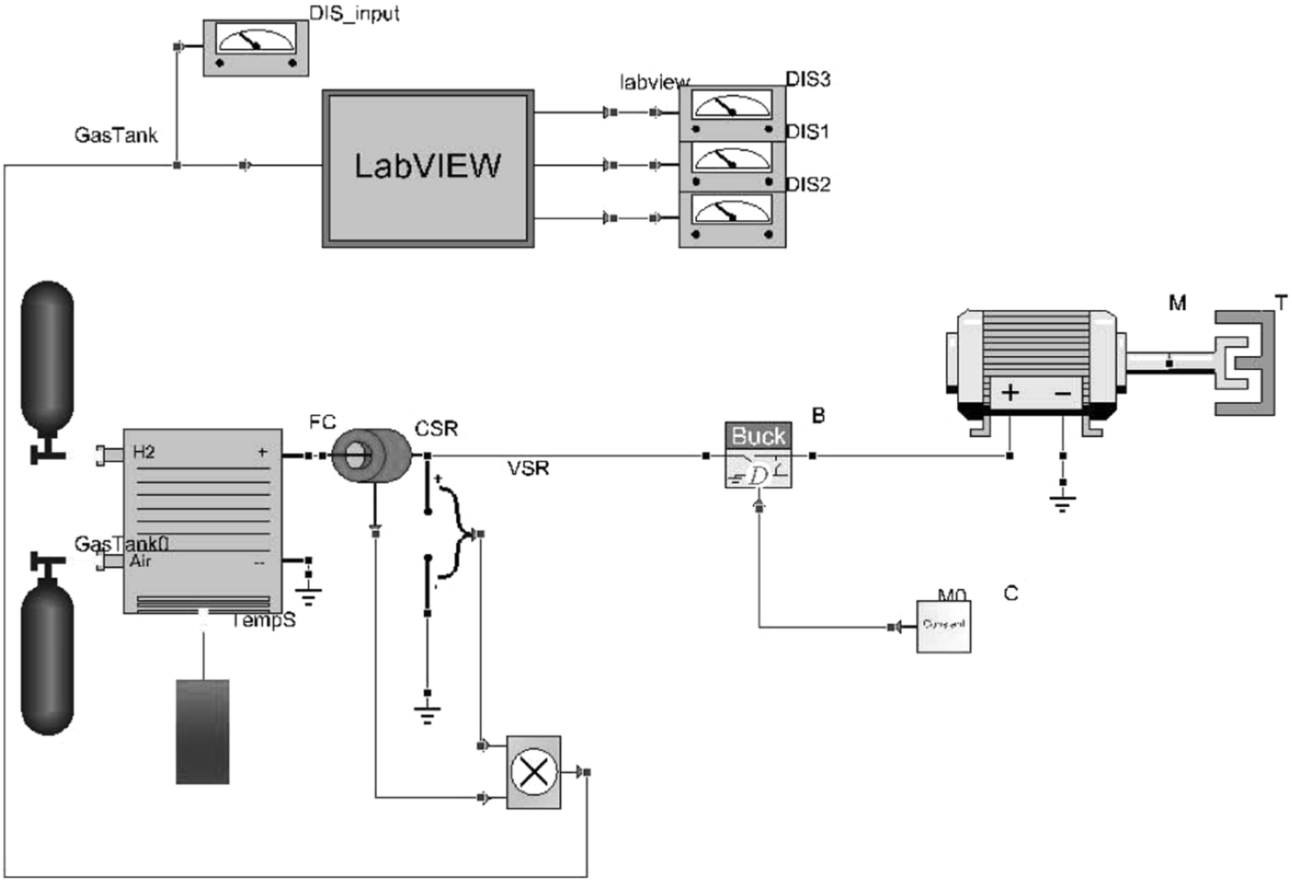


Fig. 11. VTB schematic of the system under test; notice the LabView interface block to control the hardware programmable load to demand the simulated power, the fuel cell model on the left with thermal and fluid connections.

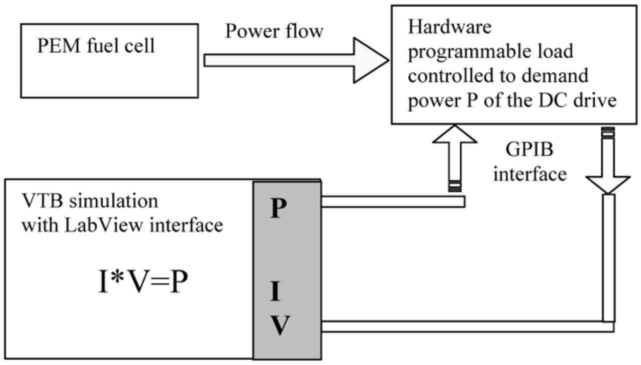


Fig. 12. Scheme of the experimental setup.

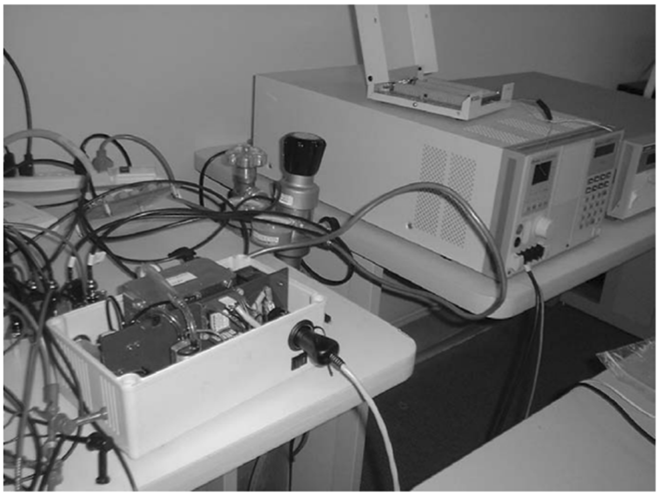


Fig. 13. The programmable load on the right, the fuel cell on the left.

design of the load characteristic to fully exploit but not exceed the power and dynamic characteristics of the fuel cell.

The power source is a 50 W proton exchange membrane (PEM) fuel cell with a no-load voltage of 24 V. The programmable load is a 300 W Chroma 63 103.

Coming to the simulated load, we adopted a dc motor with a rated voltage of 15 V, loaded with viscous friction of 0.002 Nms/rad. The buck converter is an averaged model with equivalent loss resistance of 1 $\mathrm{m}\Omega$.

The hardware setup is shown in Fig. 13.

The experiment is performed as follows. The VTB simulation is executed. The calculated current and power at the interface between fuel cell and dc drive are the input of the LabView block (see Fig. 11) that performs the interaction between VTB and the physical world. The LabView block sends the power requirement to the programmable load via the general-purpose interface bus (GPIB). The programmable load drains power from the PEM fuel cell. The fuel cell current is measured and compared with the simulated current. The simulated motor load and speed (duty cycle of the buck converter) are subject to step changes, to check the dynamic behavior of the system.

The results reported in Figs. 14 and 15 allow the designer to evaluate the performance of the system. First, we notice that the measured and simulated fuel cell current satisfactorily match; therefore the model used for the fuel cell is reliable. Conversely, the hardware fuel cell matches the expected design behavior.

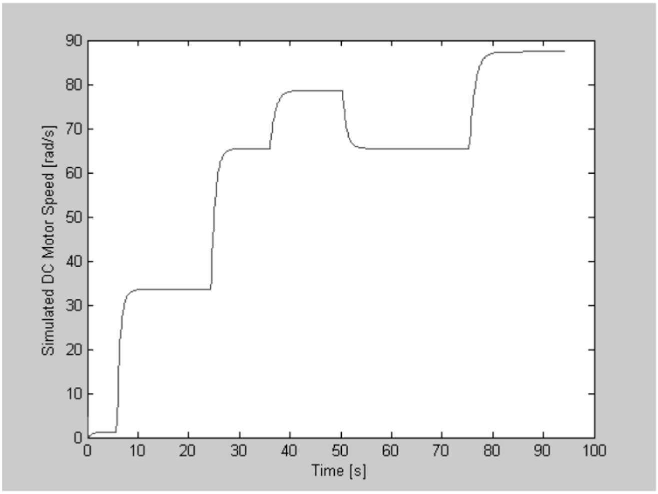


Fig. 14. Profile of the motor speed during testing; the system goes though a number of step changes, consequently varying the power demand and highlighting the transients.

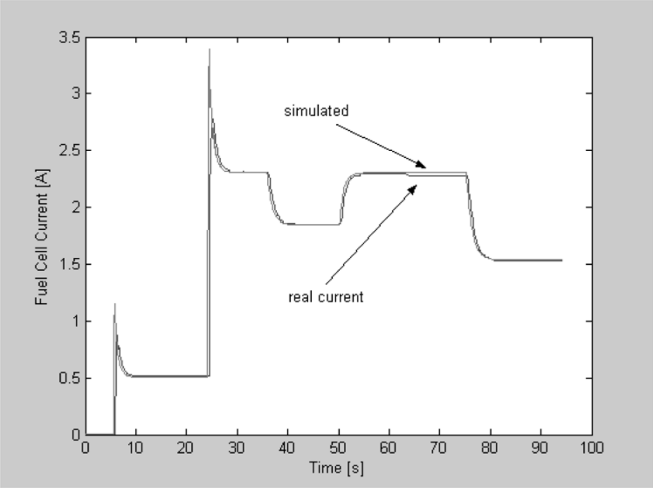


Fig. 15. Measured and simulated current of the fuel cell.

The experimental system operation can be clearly seen looking at Figs. 14 and 15. At times $t = 5$ s and $t = 25$ s a step is imposed on the duty cycle of the buck converter with no change in the motor load. This results in step changes of the fuel cell current with local considerable peaks. The motor load undergoes step changes at $t = 35$ s (decrement), $t = 50$ s (increment), and $t = 75$ s (decrement). This result in step changes of the fuel cell current, but this time no local current peaks are visible. The result is particularly significant from the design point of view, since fuel cells are sensitive to high currents. The simulated peak could faithfully provide information about the feasibility of speed changes in the motor that may result in dangerous current peaks. Notice that the simulated current peak is larger that the actual current peak. This is due to the controlled programmable load that replaces the actual drive in the physical experiment.

From Fig. 14 we can also verify that the fuel cell is keeping up with the dynamic of the load. From the point of view of the designer that relies on incremental prototyping, the simulated fuel cell represents the desired characteristic; therefore a mismatch

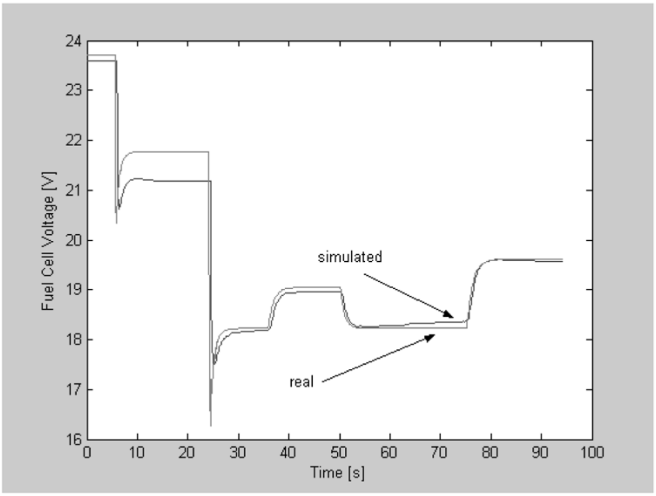


Fig. 16. Measured and simulated voltage of the fuel cell.

between simulated and measured current during this dynamic performance would lead the designer to the conclusion that the physical fuel cell can not sustain the dynamic of the load.

Finally Fig. 16 shows the fuel cell voltage dynamic. This is a very significant quantity for the specific application. The designer can appreciate how the load is going to affect the output voltage of the fuel cell under the real dynamic conditions.

This experiment, in particular, was carried out with the electrical drive operating in open loop to allow for slow dynamics. The maximum dynamic performance that can be tested with this experimental setup is limited due to the internal programmable load control dynamic and the GPIB communication, which is the actual bottleneck. These limitations are related to the specific experimental setup used here, not to the approach itself, which is independent from the actual implementation.

From the designer standpoint, the experimental results in summary indicate:

- the value of viscous friction that can load the motor drive without damaging the fuel cell or interrupting the service;
- the effects of the drive control strategies on the fuel cell current local peaks;
- the dynamic compatibility of the power source and the load.

VII. CONCLUSION

A first realization of a VE able to acquire real signals from a remote DUT has been proposed and tested for model validation and complex system design purpose.

The preliminary results show the feasibility of this solution and are extremely encouraging toward further developments of the VTB-LabView partnership. In particular, this paper detailed the application of the approach to model validation for two simple example systems. The results obtained from the two simple case studies indicate that the approach is promising. The results obtained from the complex system of the fuel cell supplying a dc motor drive show that the approach is particularly suitable for incremental prototyping of complex systems. The described approach can be extended to systems with much faster dynamic behavior and more complex setup. The only limitations that were highlighted in Section VI are not due to the VE approach itself, but are due to the bandwidth of the particular experimental setup adopted in this work. To overcome these limitations and to create the most suitable environment for the described approach, the authors are currently designing and building in-house a platform for incremental rapid virtual prototyping and testing. The new platform will allow for much higher bandwidth and will be dedicated to high-performance multisource power source systems, which is a major area of interest in the research group of the authors at USC.

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