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Cyber-Physical Testbed Co-simulation Real-Time: System Frequency Response

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Abstract—Future carbon-neutral power systems impose many challenges; one of them is an advanced simulation platform that allows replicating the complex systems' actual dynamic performance. DIGEnSys-Lab is working toward proposing solutions to the most critical challenges to carbon-neutral energy systems. This paper shows preliminary results of implementing a cyber-physical testbed co-simulation real-time dedicated to analysing system frequency response. The testbed is a cyber-physical system where the physical layer is represented by two real-time simulators in a closed loop: Typhoon HIL 604 and Opal-RT OP4510. The cybernetic layer is used to model a test system and to control the real-time simulation. This paper shows the results of the system frequency response of a modified version of the P.M Anderson 9-bus system using phasor measurement units. Simulation results show the appropriate performance of the proposed testbed.

Keywords—Co-simulation, hardware-in-the-loop, low inertia power systems, real-time, system frequency response.

I. INTRODUCTION

Power systems are evolving at breakneck speed toward reaching a carbon-neutral status. Massive energy integration from renewable sources displaces conventional synchronous units from the generation mix, causing several challenges for the secure and economical operation of the electrical power systems, such as reducing the short circuit level, system strength reduction, and reduction in the total inertia of the system, etc. The dramatic reduction of the system rotational (mechanical) inertia and system strength makes the power system dynamic volatile, with more extreme deviations and speed. Therefore, power systems engineers must consider departing from the classical off-line simulations, and more realistic simulation tools need to be used adequately to study the impact of this inertia loss and establish the guidelines for the proper development of future power systems [1].

In this sense, *real-time simulations* (RTS) have been erected as the fundamental tool for testing computer models of physical systems. When the physical system is an electric power system, RTS is a technique for the transient simulation using digital-computer time-domain solution [2]. However,

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RTS provide an umbrella for two categories of studies considering the physical domain: (i) fully digital real-time simulation that includes paradigms such as model-in-the-loop, software-in-the-loop, or processor in-the-loop), and (ii) hardware-in-the-loop (HIL) real-time. In the latest one, part of the system (including control, protection, and other accessories) is modelled in the cybernetic layer and run in the real-time simulator and the physical layer is a real physical device involving interfacing or input/outputs (I/Os).

The DIGEnSys-Lab was established in January 2021 (see website: <https://fglongattlab.fglongatt.org>). The acronym stands for DIGEnSys-Lab = Digital Energy Systems and Lab, the shortest for Laboratory. This is the name of the real-time hardware-in-the-loop laboratory facility built for research and also the Prof FGL research group (fglongatt-Lab). The laboratory infrastructure includes state of the art facilities and equipment for real-time simulation in a cyber-physical fashion to investigate and propose solutions to the most critical challenges to the carbon-neutral energy systems.

One of the challenges is the reduced rotational inertia and its impact on the power system frequency response. The authors are embarked on developing a platform for conducting rigorous, transparent, and replicable testing of scientific theories, computational tools, and innovative technologies. This scientific paper is dedicated to showing preliminary results of the implementation of a cyber-physical testbed co-simulation real-time dedicated to the analysis of system frequency response. The test best is intended to use a real-time simulation approach to obtaining the system frequency response of a representative test system when subject to a frequency disturbance (sudden generator outage or load disconnection). There is a large number of publications dedicated to showing real-time testbeds, some of them specifically dedicated to rapid prototyping [3,4], control in the loop [5,6], cyber aspects of power system [7,8], cyber-security [9,10], etc. This scientific paper is different from all the previously published papers as this is dedicated explicitly to frequency response and considers co-simulation using two real-time simulators (different vendors) in a close loop. The main advantage of using two real-time simulators from different vendors is to provide scalability, flexibility and reliability to the testbed. Consequently, power systems can be modelled with a deeper level of detail, which means greater

fidelity. Furthermore, the computational capacity is improved, being each real-time simulator more adequate for different specific tasks.

Section II presents the motivation of the cyber-physical testbed and different elements composing the layers; Section III briefly explain the implementation and Section IV show simulation and results of the proposed testbed. Finally, Section V presents the conclusions of the work.

II. CYBER-PHYSICAL MODELLING

The proposed cyber-physical testbed co-simulation real-time dedicated to analysing system frequency response consists of two layers: (A) a cybernetic layer and (B) a physical one. The cybernetic layer consists of the control and communication elements of the test best; it includes the software used to control and operate the physical layer, especially the software used for modelling and simulation of the power system test system. For simplicity, all the software in the cybernetic layer is run, and they operate from the Host PC (depicted in Figure 1). The physical layer involves the hardware used in the testbed, as shown in Figure 1, and it consists of two different vendors digital real-time simulators (Typhoon HIL and OPAL-RT), the wired interface used to interconnect the analogue I/O of the simulators. In addition, an oscilloscope is used to capture signals in the close loop between the simulators. The rationale behind using two-real time simulators in a co-simulation framework and closing the loop by using analogue electrical signals (voltages) is to provide the flexibility to expand the testbed to hardware in the loop (HIL). DIgEnSys-Lab is equipped with physical devices for measurement, control and protection, including phasor measurement units (PMU) and merging units, and the idea is to use the analogue signals to feed them in the future developments of the testbed. The following subsections provide more details regarding the modelling used in each of these layers with their main components.

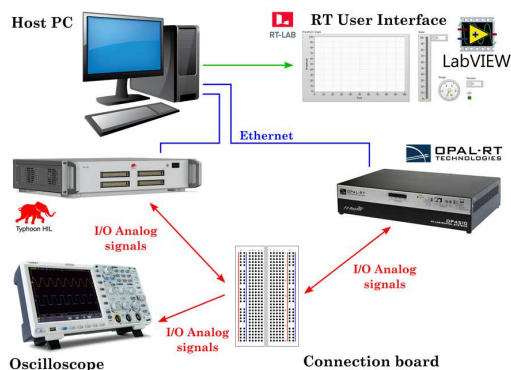


Fig. 1. General structure of the cyber-physical test bed co-simulation Real-Time for system frequency response.

A. Cyber Layer

As previously mentioned, the cyber layer is located inside the Host PC and includes software required for modelling/simulation but also to control the digital real-time simulators. The Host PC is based on an operating system Microsoft Windows 10 Home; for simplicity, in the design of the testbed, the proprietary software for modelling/simulation and running/control of the real-time simulators are running in the same PC. Typhoon HIL Control Centre 2021.4 and OPAL-RT RT-Lab 2021.3.2 are used for the Typhoon HIL 604 and the OPAL-RT OP4510, respectively.

In this preliminary version of the testbed, a test system is implemented in the OPAL-RT RT-Lab 2021.3.2, and the Typhoon HIL framework is used to close the loop by sensing and producing feedback signals.

1) Test System

In this paper, a simplified version of the Western System Coordinating Council (WSCC), as described in [11] (see Fig. 2), is used as the test system. It consists of three synchronous generators, three static loads, three two-windings power transformers and a transmission system in 230 kV. The original test system has been slightly modified: the loads have been deliberately modelled as constant impedance, and its load reduced by 20% and the two-winding power transformers are considered connected following the Yy0 vector group.

As the main interest of the proposed testbed is to mimic a real system during a frequency event, the system is equipped with measurements devices, as a consequence, all the system's buses have been equipped with Phasor Measurement Units (PMUs) to provide measurements of voltage magnitudes (V_{abc}), voltage angles (Φ_{abc}) and frequency at each measurement point. A three-phase-locked loop was used to represent PMUs, which calculates the positive-sequence component of the input three-phase signal over a running window.

Typical system frequency response is excited by a frequency disturbance. In this testbed, the authors decided to include two types of single contingency events: (i) sudden disconnection of a specific load and (ii) sudden disconnection of one synchronous generation unit. As a consequence, the test system is equipped with six (06) three-phase circuit breakers (CB), each breaker will allow the disconnection of one power equipment (generator or load) during the course of the real-time simulation allows the capture of the real-time signals of the system frequency disturbance.

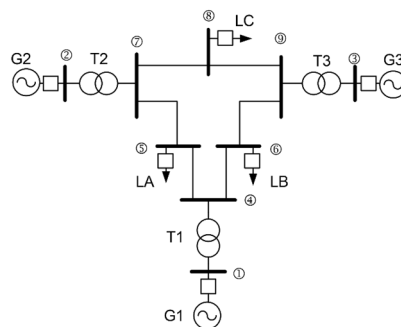


Fig. 2. Test system: a modified version of the P. M. Anderson 9-bus test system [11].

2) Monitoring and control system

The monitoring and control system is a Graphic User Interface (GUI) that allows to visualise and control simulations in real-time. In particular, this GUI is customised to present the signals generated by PMUs as measurements of the electrical signals in the test system during the real-time simulation, also the GUI graphically presents the actual status of the six circuit breakers installed in the test system and the numerical values of the rotational inertia constant (H in sec) of each synchronous generator are presented. On the other hand, the GUI is designed to execute control commands in the test model during the real-time simulation by an appropriate flow of signals. The customise GUI provides complete user control on the status (open/close) on each of the circuit

breakers installed in load and generators, all of this to allow the user to insert a single contingency (generator disconnection or load disconnection).

The GUI includes the possibility of modifying the rotational inertia constant of each generator during the real-time simulation. The authors recognise that is not a realistic disturbance, and it is not intended to do so. Instead, it is included as an option for the user to set the value of the rotational inertia of each generator before inserting the disturbance; it will allow the user to define scenarios with different inertia without the need to stop the real-time simulation and compile/rebuild the simulation model.

B. Physical layer

The physical layer is where the co-simulation environment occurs, with two non-synchronised real-time simulators (two different vendors) executed separately, exchanging only I/O voltage analogue signals using traditional copper wires, and an oscilloscope is used to record physical voltage signals during the real-time simulation. The two real-time simulators in the close-loop co-simulation environments are: (i) OP-4510 from the company Opal-RT, which consist of the main CPU based on Xeon four-core processors and a powerful Xilinx Kintex 7 FPGA; also it includes digital and analogue I/O. (ii) HIL 604 from the company Typhoon HIL includes 8 processing cores; 2 ARM cores, and digital and analogue I/O. The loop between the real-time simulators is closed by a galvanic connection using copper wires and a breadboard interconnecting their I/O analogue cards. In the physical layer, an oscilloscope (Tektronix TBS 1052B-EDU) is installed to allow displaying and recording voltage analogue signals exchanged in the closed-loop. Both simulators configuration and execution of both simulators are controlled from the Host PC running the appropriate proprietary software (it is discussed in the next section). The Host PC is a workstation based on Ryzen 9 3900X (12 cores), 16GB of RAM memory, 1TB SSD GeForce RTX 2070 SUPER; the computer has an operating system Microsoft Windows 10.

III. IMPLEMENTATION

A. Cyber layer

The cybernetic layer is used to create the power system model, define signal flows (I/O), the customised GUI. The test system was initially developed using MATLAB Simulink R2019b and then transferred into the OPAL-RT proprietary software RT-Lab v2021.2.0.244. The customised GUI was created using LabView 2017 (32 bits), which is fully integrated into RT-LAB. Typhoon HIL Control Centre 2021.4 toolchain has been used to receive an analogue signal, measure and send then as analogue output. The following subsections show the implementation steps of the test system and the monitoring and control system (GUI).

1) Test system

The model of the 9-bus test system has been implemented in MATLAB/Simulink (version R2019b), which makes it really easy to be imported into the RT-Lab simulation environment. The Simulink file (.slx) needs to be appropriately separated into subsystems for real-time simulations in RT-Lab. In this very specific, two subsystems have been defined: *SM_Master* subsystem, which is the core of the simulation, and the *SC_Console* subsystem, designed for monitoring purposes. The implemented model is able to

run at a fixed step size of $T_s = 173.6 \mu\text{s}$ using Euler's method as a solver. The test system is located in the *SM_Master* subsystem (see Fig. 3), together with several blocks whose functions are specified below:

- *OpCtrl*: controls the programming of OPAL-RT cards by the bitstream file and selects its hardware synchronisation mode. This block is required because it tells the FPGA card where to expect inputs and where to transmit outputs and perform operations on the signals in between.
- *OpMonitor*: gives timing information about the model, such as the computation time, the idle time, or the number of overruns. The information provided by the OpMonitor block is used to determine if simulations are running in real-time.
- *OpWriteFile*: saves the input signals to a file. This block is useful for post-processing the simulation results. In this work, the OpWriteFile block was used to save the cyber and analog versions measurements from the PMUs.
- *AnalogOut*: transmit signals of the model to a physical I/O card in the form of output voltages. It also defines the *DataIn* port number of the bitstream file, the number of *AOut* channels and the voltage range of the output voltages. These voltages can be measured on the Slot 2 Module B Subsection 1 of the Opal-RT 4510 simulator.
- *AnalogIn*: returns voltages values from Analog Input channels of a physical I/O card. It also defines the *DataOut* port number of the bitstream file and the number of *AIIn* channels. These voltages can be measured on the Slot 2 Module A Subsection 1 of the Opal-RT 4510 simulator.

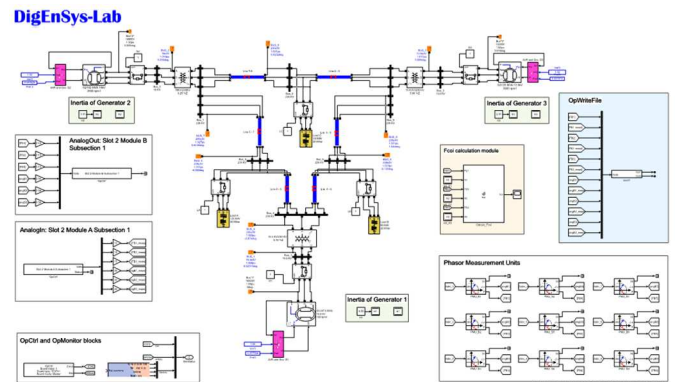


Fig. 3. Overview of the *SM_Master* subsystem, which includes the test system and additional blocks used in the Real-Time simulation.

- *Phasor Measurement Units*: compute magnitude, phase, and frequency of the positive sequence component of a three-phase signal. This block is inspired by the IEEE Std C37.118.1-2011 [12]. The model includes 9 PMUs to measure these magnitudes in all the buses. This block requires as parameters the nominal frequency f_n of the system (60 Hz) and the sampling rate N_{sr} of the signal (points/cycle). In this work, a sampling rate of 24 points/cycle has been chosen. The most significant step size permitted for simulation is determined by the nominal frequency of the system and the number of points per cycle, which is defined by $T_{s,max} = 1/f_n/N_{sr} = 694.4 \mu\text{s}$. However, as previously stated, $T_s = 173.6 \mu\text{s}$ was chosen as the step size in this study in order to properly characterise the test system's performance. It is worth noting that T_s needs to be a submultiple of $T_{s,max}$.
- *Calculation module for the frequency of the center of inertia (f_{co})*. This value is the frequency weighted by

rotation inertia at different locations across the power system. In this work, the f_{Col} has been calculated as:

$$f_{Col} = \frac{1}{\sum_i^{N_g} H_i} \sum_i^{N_g} f_i H_i \quad (1.1)$$

where f_i is the frequency measured at the i -th generator, and H_i is the rotational inertia coefficient of the i -th generator and N_g is the total number of generators ($N_g = 3$, in this test system).

- *Modules to change the inertia of the generators.* These modules allow the modification of the inertia from the GUI during RT simulations or between them.

2) Monitoring and control system

The feature of monitoring and controlling a real-time simulation is integrated into RT-Lab by using LabView panels. The first step in the design of a LabView panel consists of the creation of the *virtual instrument* (.vi) file. Then, from the control palette, a wide variety of control and indicators items, including numeric, Boolean, string or graphical elements, can be added to the panel by simply dragging and dropping. Once the panel is configured, saved, and opened in RT-Lab, the assignment of the signals and variables from the Simulink model to different elements of the panel can be done. If the RT-Lab model is already compiled, the variables and signals must appear on the corresponding subsystem of the Project Explorer. Then, the assignment is made by dragging the variables and signals from the *Project Explorer* and dropping them on the corresponding elements of the panel. Fig. 4 shows the panel designed for this work. It includes the following items:

- *Push Buttons:* allow opening and closing of the three-phase breakers, producing power imbalances and, therefore, exciting the system frequency response.
- *Square LEDs:* indicate the state of the breakers. This information is useful to identify when a switch is opened or closed during RT simulations (green: open, red: closed).
- *Numerical controls:* modify the coefficient of inertia of the synchronous generators by introducing a new value. This functionality is useful to compare different scenarios with high or low inertia.

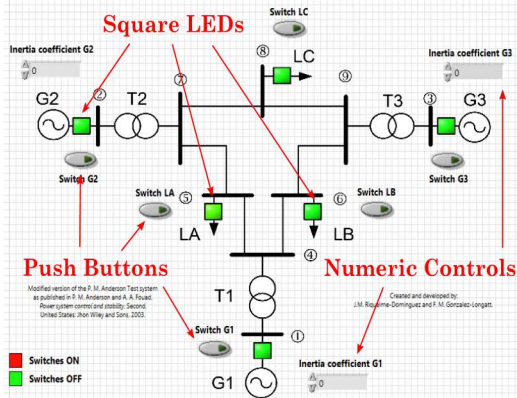


Fig. 4. Configuration of the LabView panel, including squared LEDs, pushbuttons and numeric controls.

B. Physical layer

The physical layer is implemented by wiring the analogue outputs and analogue inputs between the real-time simulator. The analogue output of the real-time simulator Opal-RT 4510

consists of signals at the terminal marked positive (1+,2+, ...,6+) together with a common ground terminal (GND). These channels are used to send the signals of the generator buses' frequencies (f_{B1}, f_{B2}, f_{B3}) and respective voltage angles ($ang_{B1}, ang_{B2}, ang_{B3}$) to the real-time simulator Typhoon HIL 604. Typhoon HIL real-time simulator receives these signals in the Analog Input Indexes $A119$ to $A124$. The signals are directly sent from the Schematic Editor to the HIL SCADA, without any kind of signal processing, from where they are sent again from ports $AO33$ to $AO38$ in the form of analogue signals to Opal-RT real-time simulator. In this way, the co-simulation loop is closed, and the analogue signals can be registered and compared with their cyber version. Although at this moment, the function of the Typhoon HIL simulator consists only in receiving and sending the analogue version of cyber signals, the RT co-simulation platform is prepared for implementing another kind of controls from that simulator in the future, as for example, load shedding control when an under frequency event occurs. Fig. 5 shows the actual experimental setup of the physical layer, with the main components and signals highlighted.

IV. SIMULATION AND RESULTS

This section is dedicated to illustrating and showing the operation of the proposed cyber-physical testbed co-simulation in real-time for the analysis of system frequency response. The real-time co-simulation platform is illustrated in this section by running a real-time simulation and exciting a system frequency disturbance, specifically by considering the sudden loss of a generating unit.

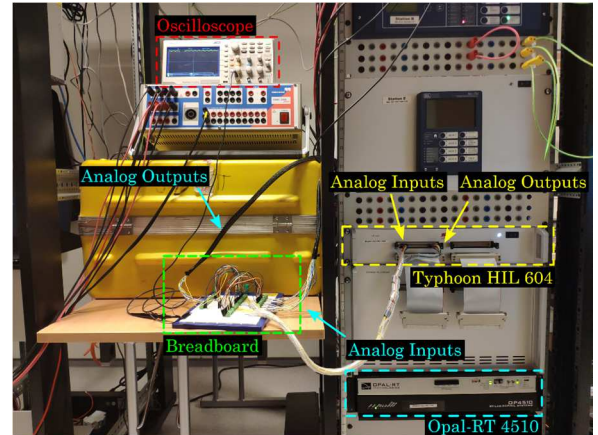


Fig. 5. Experimental setup of the physical layer. The Host PC is not depicted here.

The test was conducted in the following manner: initially, the three synchronous generators and the three loads are connected (switches ON, red colour), during these conditions, the test system is operating a steady-state condition, and the frequency is approximately 60 Hz (some minor noise coming from the analogy measurement). Subsequently, the user uses the GUI to open the circuit breaker connecting generator G1 to the grid, the breaker opens at $t = 27.0$ sec (in this specific simulation), resulting in an imbalance between generation and demand, and the total system inertia is reduced by the disconnection of generator 1 ($H_1 = 9.55$ seconds). From that moment on, an under frequency event occurs, reaching the minimum frequency $f_{min} = 57.08$ Hz in 3.25 seconds. This situation is maintained to the end of the simulation ($t = 100$ sec). Fig. 8 shows the view of the GUI during the RT simulation. As depicted, the interface represents the breakers'

states of the system (with the switch of G1 already in green) and the evolution of the system's frequency during the event. Fig 6 compares the evolution of the frequency in its analogue and cyber versions. Finally, Fig. 7 shows the detail of the system frequency response of Bus 1 in a small-time window around $t = 27.25$ sec, the moment that circuit breaker 1 is opened.

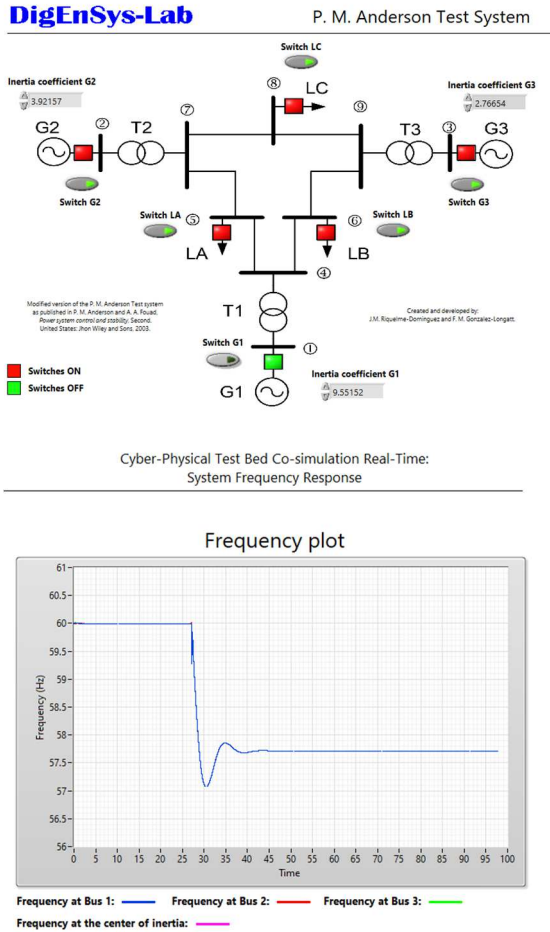


Fig. 6. View of the GUI during the RT simulation: On the top, the real-time state of the test system and, on the bottom, the test system frequency response.

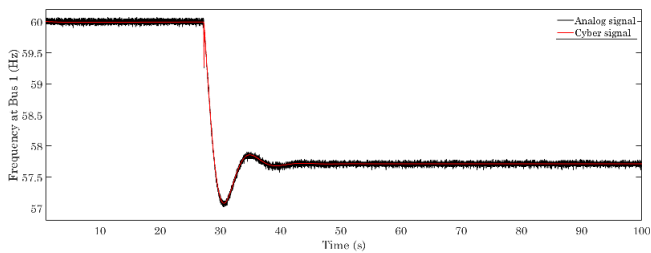


Fig. 7. System frequency response at Bus 1 following the sudden disconnection of G1 at $t = 27.25$ sec. Frequency's cyber signal vs analogue signal.

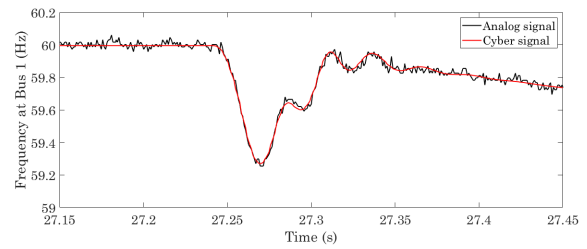


Fig. 8. Detail of the system frequency response of Bus 1 at $t = 27.25$ seconds. Frequency's cyber signal vs analogue signal.

V. CONCLUSIONS

Future carbon-neutral power systems face multiple problems, one of which is the development of an advanced simulation platform capable of simulating the real-time dynamic performance of complex systems. In this sense, DigEnSys-Lab is working on building a flexible real-time co-simulation environment. This paper presents the preliminary results of the implementation of a cyber-physical testbed co-simulation real-time dedicated to the analysis of system frequency response. The testbed consists of a cyber-physical system with two real-time simulators in a closed-loop representing the physical layer: Typhoon HIL 604 and Opal-RT OP4510. The cybernetic layer is used to implement the test system and to control real-time simulations. The system frequency response of a modified version of the P.M Anderson 9-bus system utilising phasor measuring units is shown. Real-Time simulation results show the flexibility of the proposed testbed and its adequacy for system frequency response studies. Future research will focus on the expansion of the testbed presented in this paper.

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