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Augmented Cyber-physical Model for Real-time Smart-grid Co-simulation

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Abstract

Due to crucial importance of the electricity in almost every aspect of our life, power systems and their components continue to receive considerable attention, and important efforts are invested for development or improvement in the direction of smooth transition to full smart grid solutions. Even if operation and control of power system are well-known, new control solutions require careful and detailed investigations due to challenges emerged from high complexity, security or even the current operating conditions in high penetration of renewable energy sources or consummers with significant loads. In this context, the paper introduces a new concept and solution of augmented cyberphysical model to allow testing and simulation of the supervision, monitoring and control solutions in a mixed physical and virtual environment, facilitating complex investigation starting from common process level to complex interdependencies arise from communication infrastructure inherent failures to contingent issues such as software related or security attacks. The concept, architecture and an implementation on a real-time hardware-in-the-loop based platform are revealed and shown as an open and affordable research and development solution.

Keywords: augmented cyber-physical system, real-time simulation, co-simulation smart grid system advanced control.

1 Introduction

One of the most important dependencies in the humankind usage is represented by the electricity that did not suffered significant changes on its form, but of which demand and way of delivery evolved in significant ways. As examples the power flow control through the aim of new technologies related to the information technology and communications and power electronics enabling new services for consumers and enhanced electricity handling correlated with primary resources availability can be mentioned.

The highest level reached is represented by what we now call the smart grids, complex structures that unite distributed production systems, various storage systems, up to smart or traditional consumers, together with the entire information and communications infrastructure. The management of such configurations, whether in the design or operation phase, requires systematic approaches but also adequate support tools for the easy management of complexity. The present paper aims to present precisely a concept and a unique pilot example, which could change the traditional way of supervision and monitoring by providing not only access to operating functions but also interaction in an ontological cognitive ergonomic context specific to smart grids.

Concerns regarding the enhancement of human operation in the field of power systems related to electricity production have existed for almost three decades. The context was just different, in the sense that the aim was to ensure the safety of the human operators through teleoperation in hazardous environments. Goto et al. in [9] propose such a solution for the handling of radioactive material in nuclear power plants. Research in this direction has continued since then and current concerns, such as those proposed in [10, 12] can be found.

In the literature, specific proposals related to the robotic maintenance of power line such as Wand et al. in [21] as an example can be found, proposals developed for risk areas, where teleoperation, respectively monitoring or control through specific virtual reality and mixed reality technologies represent a necessity.

Of course, from the list of performed investigations, those dedicated to the training and upskilling of operators and specialists in the energy field should not be neglected. As examples the case of training technical skills in maintenance of live-wire in distribution grids [14, 18] or the one related to advanced approaches such as the digital twin for electrical networks proposed by [6] can be mentioned.

Complementary to the previously mentioned directions, this paper proposes a useful solution in both training, modelling, simulation and analysis focused on smart grid systems. The necessity and role of such a proposal is detailed in the next chapter.

The paper is further structured as follows: section 2 analyses smart-grids development towards new challenges of modern power systems, followed by the detailing of the proposed concept in section 3: Augmented Cyber-physical System for New Smart-grids Services Design and Implementation and a case study, the last part being dedicated to the conclusions and perspectives for improving the proposed system.

2 Smart-grids Development Towards New Challenges of Modern Power Systems

The development of new technologies is one of the stimulating factors for the development of competitive solutions, adapted to new market requirements or in accordance with regulations. The evolution of energy systems has also followed the same model. However, the evolution and development of these systems has been accompanied by various and numerous challenges. Smart grids started, for example, from models such as perfect power proposed by Galvin and Yeager [7], active networks or self-healing networks [16] but which, in order to be developed, assumed a transition to the level of ambitions of using distributed sources correlated with the availability of primary renewable energy resources, something quite difficult to achieve in a first stage. This was also caused by the impossibility of addressing the imposed requirements only by implementing advanced management and control systems. It is thus imperative to note the need for evolution on several levels: the structural (of physical elements), the higher-level, informational, and the policy level, including fair access to the energy [8].

The evolution of classical infrastructure to the stage of current smart grids can be seen in Figure 1 where specific smart grid structures are highlighted. Distributed generation systems, such as solar panels and wind turbines, smart consumers and systems based on advanced communications and control technologies are illustrated. Through an appropriate management, these systems can respond to the new challenges attributed to modern energy systems, which include the increase in energy demand, the integration of renewable energy sources and the need to reduce carbon emissions.

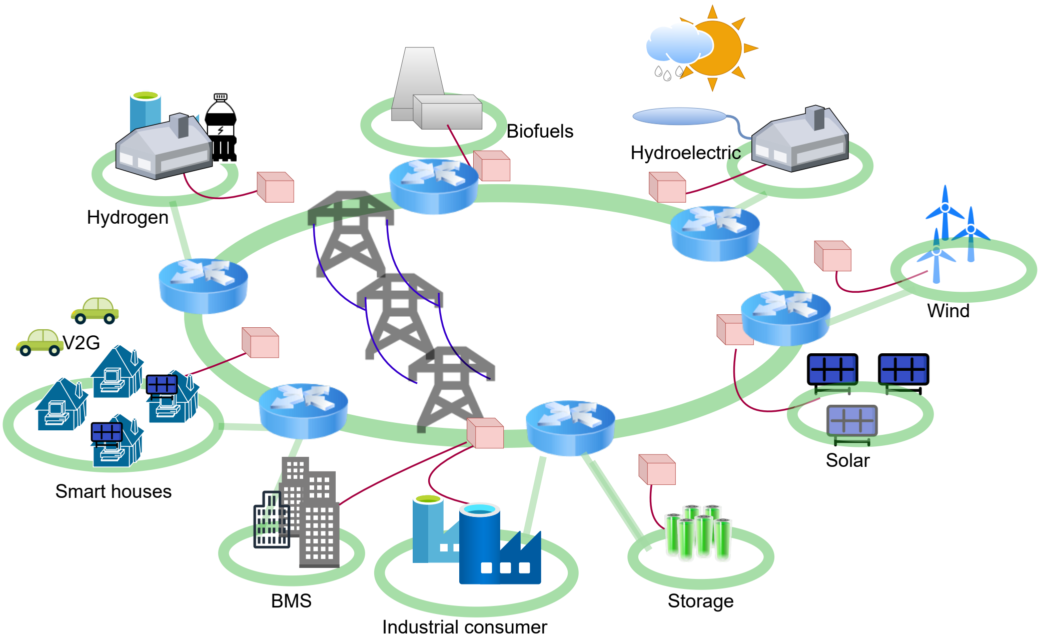

Figure 1: Smart grid infrastructure.

An important requirement of smart grids is to ensure the ability to effectively manage energy flows through the use of two-way communication technologies. These technologies allow real-time monitoring and control of energy consumption and production, thus ensuring optimal distribution and reducing the risks of network overload. Smart grids also facilitate the integration of new components such as electric vehicles and other edge technologies, with the aim of developing an energy system with increased flexibility and resilience.

The penetration of renewable resources at an increasingly high level requires the adoption of solutions to reduce the impact caused by intermittent availability. Adopting these solutions by adding new energy production systems can be an option but involves high costs, and often does not represent the most complete alternative. However, dedicated management systems or dedicated policies can bring an important benefit. For example, in the case of management systems, we can find modules that, based on models, can estimate the availability of resources or consumption needs, essential components necessary not only for the previously mentioned purpose but also for the creation of new services such as distributed energy management, demand-response or demand-side-management. These modules can become more efficient if prediction algorithms based on traditional algorithmic techniques based on time series analysis using regression models [2, 20] or, more recently, artificial intelligence techniques based on neural network structures [3, 5, 20], clustering [11] or deep learning algorithms or derivatives [1, 4, 13, 17, 23] are used.

A major benefit of smart grids is the ability to transform consumers into prosumers, i.e. users who not only consume energy but also produce and sell energy back to the grid. This not only helps stabilize the grid, but also encourages the use of renewable energy sources at the individual level. In addition, advanced data management systems allow rapid identification of problems and prompt intervention to minimize power outages.

However, implementing smart grids comes also with significant challenges. One of the main challenges is represented by cybersecurity, as smart grids are vulnerable to cyberattacks that can compromise the operation of the entire system. Also, the initial costs of implementing and upgrading the infrastructure can be quite high, requiring significant investments from governments and utility companies.

3 Augmented Cyber-physical System for New Smart-grids Services Design and Implementation

This section is dedicated to presenting the proposed solution from an architectural, functional and implementation perspective.

The proposed Augmented Cyber-physical System comes in the context of an accelerated trend towards the introduction of new technologies, performance improvement and innovation in the field of energy systems. Thus, the proposal aims to offer the following facilities:

– A new research test-bed for smart grid;

– A development and testing solution that can be used to support the transition of today's energy infrastructure to smart grid configurations;

– Offering an open architecture that allows the insertion of new technologies for real-time testing and simulation in smart grid operation optimization;

– Advanced human machine interface (HMI) that relies on the newest immersive technologies, offering XR based supervisory, control, data acquisition and visualization.

These characteristics allow the study, design, development, implementation and testing of new configurations for distributed energy management, new monitoring and control solutions, automation of network subsystem functions, new demand side management solutions, expansion of functionalities by interconnecting with other systems that can significantly contribute to changing energy flows, such as electric transport, or advanced solutions in the direction of diagnosis or increasing reliability, for example through predictive maintenance algorithms and last but not least, testing of solutions in the direction of increasing the resilience and robustness of smart networks in the context of cybersecurity issues.

3.1 Concept of Augmented Cyber-physical System

If we refer to the previously mentioned challenges that the smart grid must respond to, it is of real help and even imperatively necessary to involve specific tools and technologies not only for the design and testing of new smart grid configurations, but also for solutions that provide prompt, easy-to-manage information and, above all, assistance to facilitate analysis or operation in the smart grid. This is possible, however, only if there is the possibility of integrating into existing or new architectures components based on technologies such as those in the field of advanced data analysis, artificial intelligence or immersive technologies.

To identify how to achieve such a goal, a multi-criteria analysis was carried out starting from an existing model in the Intelligent Networks laboratory within the Faculty of Engineering and Information Technology, G.E. Palade UMPhST of Targu Mures, used as a demonstration support for the proposed solution. In this sense, based on a Lukas Nuelle configuration, see Figure 2 composed of a smart grid (left) and a generation (on the right) physical modules, the functionalities available for development-testing and the complementary ones that can be added in order to add new functionalities were established.

The proposed concept is based on a software level consisting of the SCADA module, marked with (1) in Figure 2 and the software models considered as virtual components running in the Matlab/Simulink environment and on the SpeedGoat real-time simulator, respectively the physical level consisting of the digital control and protection system (2), the physical model of the transmission or distribution lines (3), the physical model of a generation component (4), which can function as a classic system or controlled renewable system models from the module (5) consisting of two advanced systems with digitally controlled power converters, this module being synchronized with the grid through the automated system (6). The system allows monitoring of parameters through digital modules remotely and locally (7).

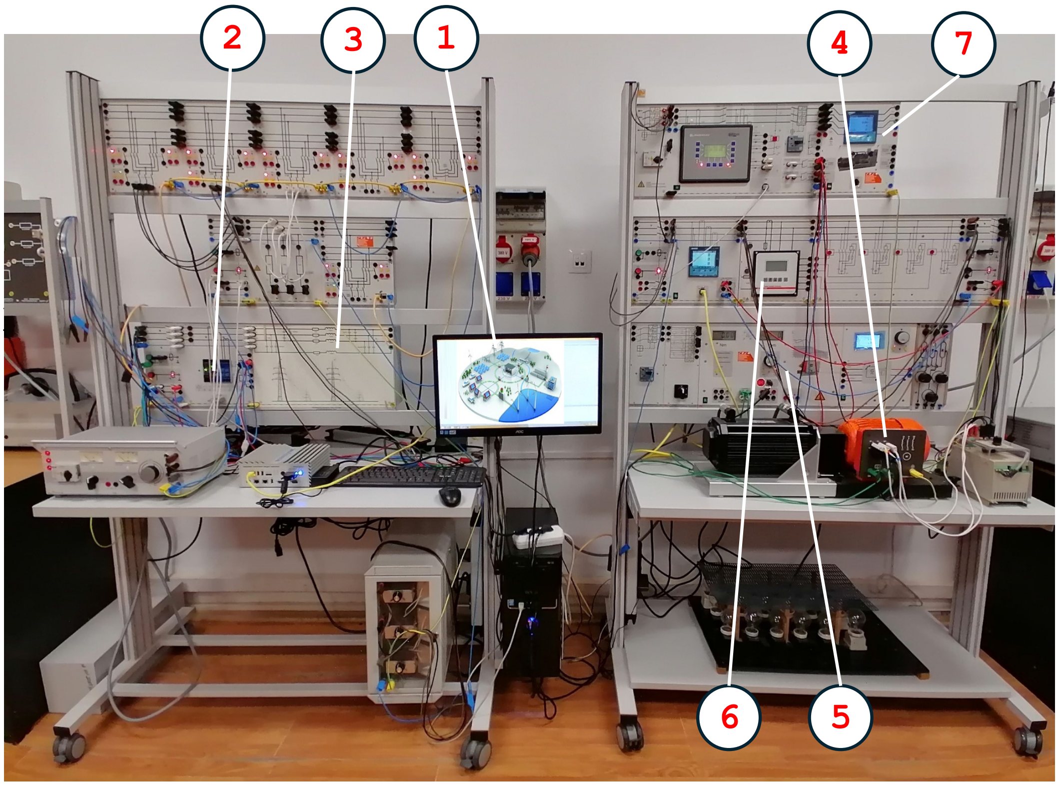

Figure 2: Concept and structure of the proposed solution.

Since adding physical modules requires time and resources, for prototyping and preliminary testing activities, virtual modules, in the form of software-implemented simulation models, we considered them to be a viable solution. Having physical simulation modules, numerical simulation, respectively hardware-in-the-loop (HIL) simulation in the structure an open co-simulation model results. This model allows varied and flexible testing depending on the needs of development or analysis.

3.2 Augmented Cyber-physical System Proposed Architecture

As mentioned above, complex functionalities, new services along with the varied and complex situations that can occur within the smart grid through the information structure generate complex data in large quantities, which can represent a challenge at the decision-making or even operational level.

To meet this requirement, the introduction of a new level specialized in data analytics and presentation into the usual architecture of a smart grid is proposed.

Considering the available structure, presented in the previous section, a new architecture was designed to include the new level of data access facilitation and assisted visualization. The structure of this architecture is illustrated in Figure 3.

In this architecture, it is proposed to model smart grids through a Physical Model module, which allows access to physical signals and parameters, including electrical signals, energy consumption, energy quality indicators, mechanical, thermal signals, etc. that influence the operation of the smart grid system. Also, to extend the model with new components for testing before resorting to the physical version, or only systems that have either a reduced influence or a complex behaviour that can be generated algorithmically, it is proposed to adopt the Cyber Model module, composed of two components: HIL module and real-time implemented models.

For the Supervisory, Control, Data Acquisition (SCADA) and Visualization level, an industrial structure used to control and manage the operation of programmable logic controllers (PLCs) as field equipment is adopted in the standard structure with field, server and HMI components.

Facilitating the presentation of data in an explicable, extensible and detailed form, along with immersive interaction, is proposed to be implemented through Augmented Monitoring, Control and

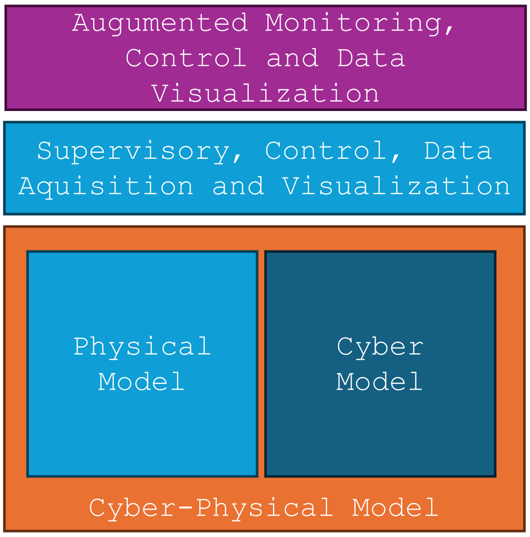

Figure 3: Augmented Cyber-physical System Architecture.

Data Visualization layer, in the current framework of advanced HMI with immersive interaction that allows complex analysis and decision making related to operational and management events.

This last layer is based both on specialized software and hardware with immersive technologies, XR and self-adapting features possible with machine learning algorithms.

3.3 Augumented Cyber-physical Services and Related Technologies

Current common interfaces are based on graphic models available on panels (display systems), in some cases with gesture interaction in the case of dedicated hardware.

Such interfaces in the case of complex systems, with numerous alarms or multiple data, present the disadvantage of difficult manipulation, often unintuitive leading to perception problems or even cognitive efficiency issues[15, 22], considered even lacking a human-centric approach [19]

New immersive technologies can address these problems and possibly even more, can provide a plus towards ensuring cognitive ergonomics. This can be achieved by multiple factors such as those though the hardware used, new software frameworks able to offer enriched experience, and more than that the diversity of of interfacing ways in the existing SCADA structures. A notable way of this interfacing solution relies on Open Platform Communication (OPC) standards.

There is also possible to use some open source solutions non-direct related to SCADA systems, such as Node-Red, that allows easy integration in advanced data storage and analytics solution such as grid and cloud computing environment.

In the framework of this work it is proposed the introduction of explainable context available through the XR technology that allows contextual related information to be offered to the operator, starting from the description of the SCADA objects for identifying roles to the mode of operation or data diagnoses. Along these, contextual decision support detailed information are provided.

All of these functionalities support safe operation, efficient tasks execution and even more reduced training periods in case of initial usage.

Classical approach often does not offer the security issues detection functionalities modules, that in case of augmented reality interfaces can be easily provided.

4 Development and testing solution for transition of nowadays energy infrastructure to smart grid configurations

In order to demonstrate the viability of the proposed proof of concept a test bed solution was developed. In the following is described the considered approach.

4.1 Proposed Solution Layout

The layout of the test-bed is organized in three components illustrated in Figure 4:

- the cyber-physical system consisting in a hardware model of power system and smart-grid layer with related software. This module also includes data acquisition system, distributed control devices and SCADA system with OPC integration;
- the co-simulation modules that consists in a real-time target machine running smart grid virtual model that includes OPC client integration;
- augmented monitoring, control and data visualization based on immersive hardware and software for implementing the advanced interaction HMI.

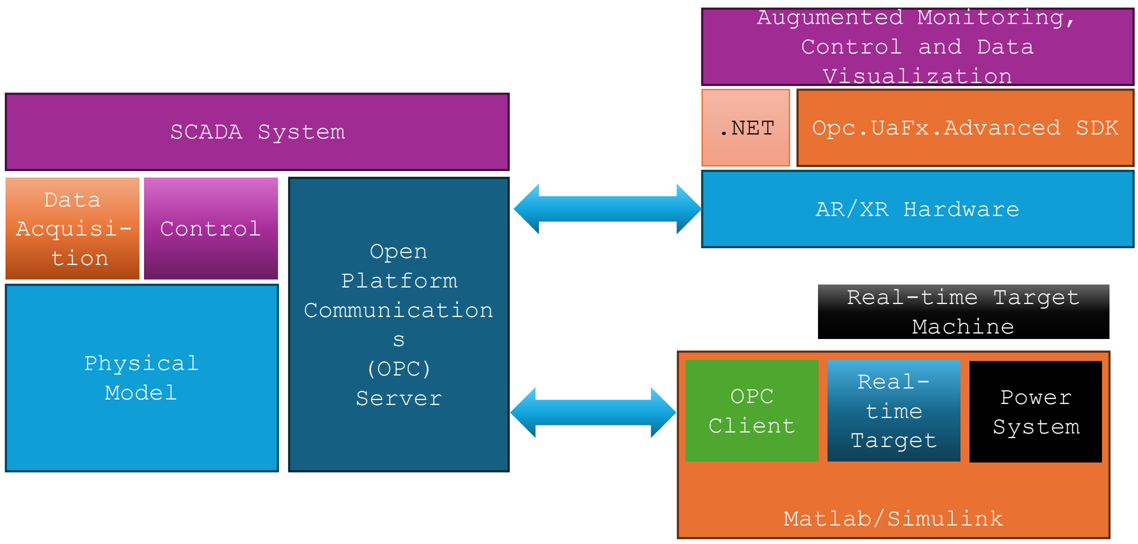

Figure 4: Augmented Cyber-physical System Layout.

The presented configuration can be operated in different simulation scenarios, either with SCADA system modules alone, with extended complementary smart grid model components and with augmented monitoring control and data visualization enabled or not based on desired running tests.

Due to modular design and inclusion of standardized interfacing offered by OPC an open solution that can be extended for considering diversified structures and systems layout is obtained.

4.2 Proposed Solution Implementation

The implementation of the test system is performed starting from the existing Cyber-Physical Model configuration that are based on substation model, generation, interconnection, protection, monitoring and control modules. On top of these is developed a SCADA system for integrated supervision, monitoring and control developed in SCADA Designer and SCADA Viewer software version 6.43 where the OPC server was integrated.

For development of augmented model that extends the physical model Matlab/Simulink version 2023a environment was adopted, with Simulink Real-Time toolbox version 2023a update 7 23.1.1 for modelling supplemental power system components that run on a Speedgoat Real-time target machine running I/O blockset version 9.6.0.1 build 30476 with 4 GbRAM and 64 Gb SSD storage.

In this configuration a custom model can be developed and for integrating in proposed architecture, this should include OPC interface model shown in Figure 5 that has to be deployed on real-time HIL simulation machine.

The advantage of proposed implementation is that based on custom requirements supplemental real-time target machines can be added due to OPC interface to the test-bed for modelling different complexity systems.

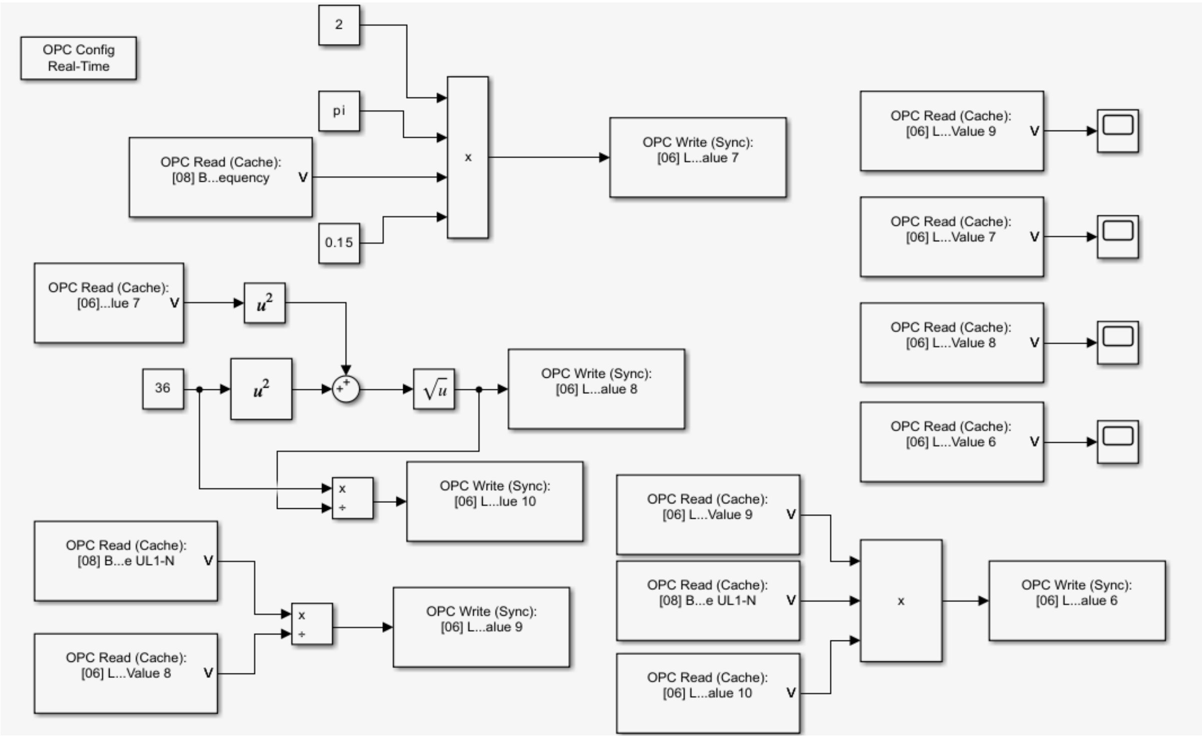

Figure 5: Matlab/Simulink model OPC integration implementation

In case of the augmented monitoring and control module the software development relies on .NET framework that run on Hololens Industrial headset enabling full access to AR/XR technology.

An example of virtual instrument implementation is illustrated in Figure 6, while Figure 7 shows augmented interaction interface during the interaction with the test-bed.

The developed solution offers few general purpose AR and XR based objects, but they can be extended for new functionalities in accordance with imposed requirements.

4.3 Augmented Cyber-physical Assessment

In order to validate the concept few assessments were proposed to be performed with the augmented test-bed. For this was adopted the following structure of the modelled system: the physical substation, equipped with monitoring and metering modules, digital control and protection system, accessible by SCADA, an interconnection physical model, a wind energy power station model with related power control unit.

Running tests with different loads monitored data were the same on classical SCADA system and in AR/XR solution. Control actions worked in both usage scenario the same. This was possible due to OPC standard integration that allows fast access to SCADA variables from and within physical model or real-time software model.

Also, a cyber-attack was simulated on one section of the power station affecting the related control modules that were disconnected causing voltage instability, as shown in Figure 8.

Before the attack affects the targeted module the line voltage can be observed in its standard range, while, at the starting of the incident, it drops to 400 V peak value. This voltage variation is reported in SCADA system and logged in the database monitoring journal.

5 Conclusion and Further Developments

In this paper, a new architecture of a development and testing system for smart grid systems is proposed. It introduces a co-simulation-based component that allows the modelling of new structures that will behave like real models. Thus, the proposed solution allows: extension of existing physical system model to a Cyber-Physical Model able to integrate new energy sources, integration of new

Figure 6: Augmented XR HMI seen from Hololens Industrial headset.

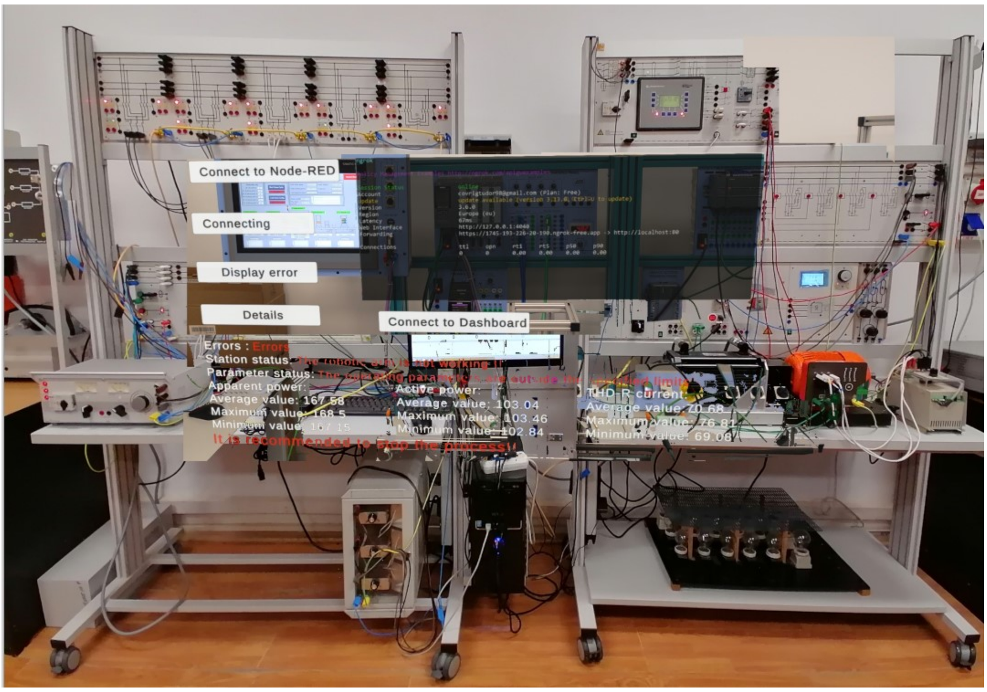

Figure 7: Testing HMI.

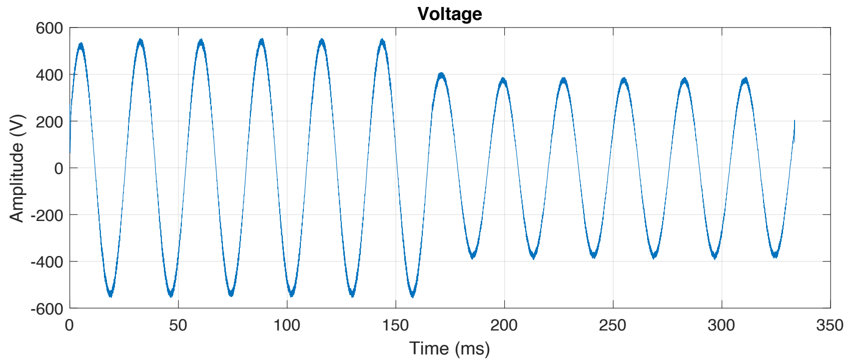

Figure 8: Line voltage evolution before and during cyber-attack.

consumers model and behaviour, implementation of control algorithm and testing through a real-time co-simulation device.

The proposed solution also offers a new type of supervisory, control, data acquisition and visualization that allows virtual model signals integration in standard configuration and also an Assistive XR HMI.

The integration in all modules of OPC standard features for communication confers to the solution an open structure characteristic.

Developed architecture offers a flexible platform for testing of new developments in control and monitoring. It can also be used as a source of reliable, unreliable or untrusted data for training artificial intelligence algorithms. Simulations and cyber-security investigations can also be performed.

In the future, an improved real-time co-simulation performance solution will be integrated and an improved two directional coupling models will be developed. Integration of new technologies such as better support for Big-Data and Data Analytics will be also investigated to be developed

Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest.

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