Development of Real-Time Digital Twins for Particle Accelerators

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***Abstract*—An experimental setup has been realised to validate the real-time communication infrastructure between the Karlsruhe Research Accelerator (KARA) and Energy Lab 2.0 (EL2.0) to develop a real-time digital twin of KARA, where the model is continuously updated by real-time measurements. The setup is equipped with high-performance Gantner Instruments, a real-time simulator, various sensors, and a control computer. The paper describes the experimental setup and presents the results of the first experiments that confirm the setup functionality.**

***Index Terms*—Digital twin of accelerator, experimental setup, measurement systems**

I. Introduction

Accelerators are complex and energy-consuming and require a stable and high-quality power supply typically provided by the public electrical grid. However, it is challenging to maintain a stable power supply due to the inability of accelerators to adjust their power requirements, mostly in the presence of a large in-flow of renewable power generation. As a result, accelerators have a negative impact on the management of the public grid since, regardless of the state of the grid (e.g., congested or under-stress), the facility still needs a steady power supply to conduct experiments effectively. In order to improve the stability and energy efficiency of accelerator operations, it is crucial to research and develop new energy solutions [1], [2], [3]. However, validating these new solutions in research facilities can be challenging, as technical issues during the validation process may disrupt research activities. To simplify the validation process, the ACCelerator Energy System Stability (ACCESS) project aims to establish a digital benchmark for accelerator facilities using the Karlsruhe Research Accelerator (KARA) as a reference and testing facility. This benchmark will be used to study, develop, and validate new energy solutions that could be difficult to test in a real facility.

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In this paper, our focus lies specifically on developing a digital replica of the KARA accelerators (digital twin) in a real-time simulation environment [4], [5]. To achieve this, we require an extensive measurement system that can constantly measure the system's status and a communication infrastructure that can send this data to the digital twin at a high sampling rate, such as 10 kHz. As KARA operates in a dynamic environment where rapid changes and fluctuations are common, having a continuous flow of measurements and transferring them at such a high speed ensures that the digital twin accurately reflects these dynamic conditions. This will enable real-time monitoring and responsive decision-making.

Moreover, KARA digital twin can be experimentally validated by means of Power Hardware In the Loop (PHIL) and explore possible flexible grid services. This can be achieved by adjusting load consumption based on market needs and integrating low-carbon technologies like photovoltaic and hydrogen-based energy storage systems [6].

Until now, no one has explored the potential of digital twins for validating energy solutions in accelerators by means of PHIL. Our approach is novel in this regard. Furthermore, the designed digital twin can be easily adapted for other synchrotron facilities such as BESSY II and PETRA III.

The paper is structured as follows. In Section II, the KITTEN experimental setup and sensor technology are defined. Section III explains the process of determining the most effective positions of electric sensors. Additionally, section IV focuses on communication between KARA and EL2.0, and presents the results of the first data package transmitted by Modbus protocol to test the functionality of the setup. Also Section V outlines our plans to upgrade the communication protocol to Ethercat. Finally, conclusions are drawn in Section VI.

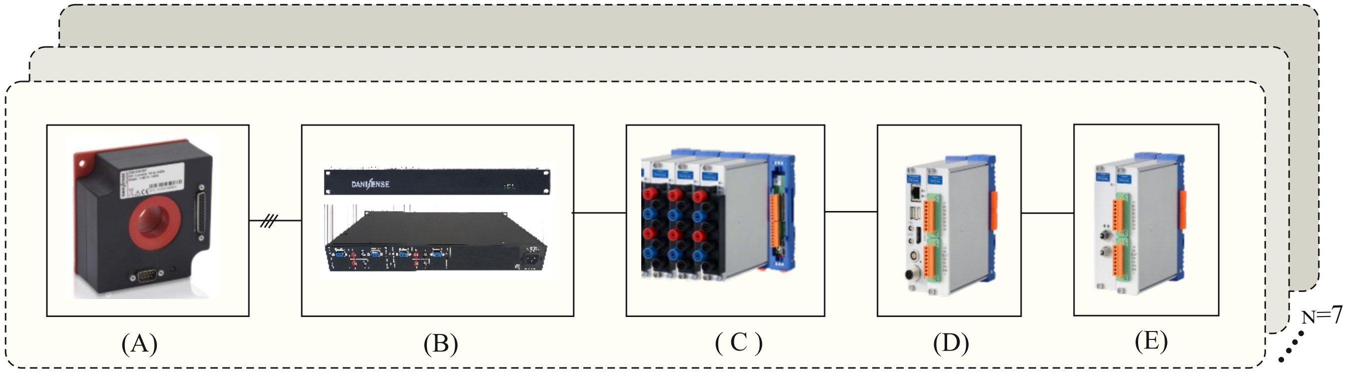

Fig. 1: Measurement system, (A) Current measurement sensor, (B) System interface unit for current transducer, (C) Q.bloxx XL A127 Module for Measuring Electrical voltage and current signal, (D) Q.station XT Controller, (E) Q.bloxx XL F100 synchronizer

II. Experimental Setup

The main aim of this paper is to present the hardware and software architecture of a system that allows for real-time communication of measured electrical parameters between two laboratories, EL2.0 and KARA, which are situated 2 km apart from each other.

The initial hardware architecture of the proposed communication infrastructure is shown in Figure 1 and consists of five main elements. From left to right: (A) the programmable contact-free flux gate-based current measurement sensor is connected to selected components to measure current up to 640 A DC; (B) the system interface unit for current transducers; (C) the Q.bloxx XL A127 SEB Module for Measuring Electrical Power profile with voltage and current measurement; (D) the Q.station XT Controller that is a high-performance edge controller for data acquisition with parallel communication over different protocol; (E) Q.bloxx XL F100 is a modular data collection device that synchronizes sensor's data in widely distributed installations, ensuring high performance and flexibility.

To provide a complete explanation, we will go in deep into each element.

A. Current measurement sensor

The Danisense DQ640ID-B is a current measurement sensor that operates without physical contact and utilizes flux gate technology. The sensor is designed to deliver high-precision and stability, especially for current measurements up to 640 A DC. It is useful for stable power supplies and as a reference transducer for calibration purposes.

This sensor comes with two important features. The first is Closed-Loop Compensation, which enhances the accuracy and stability of fluxgate sensors. In a closed-loop system, the sensor constantly monitors its output and compares it to a reference signal. Any deviation from the desired output, such as temperature changes or component variations, is considered an error. The system then adjusts the input (usually the drive current) to compensate for the error and bring the output back to the desired level. The second feature is Zero Flux Technology, which eliminates the effects of core saturation and hysteresis. The sensor core is designed to operate at a point where the net magnetic flux is zero. A feedback loop continuously adjusts the drive current to maintain this zero-flux condition. If an external magnetic field is applied, the sensor compensates by altering the drive current to keep the net flux at zero.

The flux gate sensors work on the principle of magnetic saturation. It consists of a magnetic core with primary and secondary windings. An alternating current in the primary winding drives the core into saturation in alternating directions. This saturation modulates the magnetic field in the core, which is then detected by the secondary winding. The current to be measured generates a magnetic field that alters this modulation, and the changes in the secondary winding's output are proportional to the measured current. This allows for detecting DC currents without direct electrical contact, making it ideal for isolated measurements [7].

Configuration of the DQ640ID-B is achieved through programming plug connections. Specific connections, called "CONx," are shorted to set the desired output ratio. This feature offers flexibility by allowing users to customize the sensor for their specific measurement requirements. The output ratio is adjustable from 1:40 to 1:640 in steps of 20, allowing for precise scaling of the sensor's output to match the range of the measured current. The sensor is ideal for isolated measurements where accuracy, isolation, and reliability are critical [8].

B. System interface unit for current transducer

The DSSIU-4-1U system interface unit is an essential component for Danisense's current transducer sensors as it provides power and an operational interface for up to four transducers simultaneously. This unit facilitates the connection and integration of transducers into various systems, ensuring stable and precise current measurements. It offers easy access to transducers' output signals and visual operation indicators for each connected transducer and supports a wide range of input voltages, making it a flexible solution for managing multiple current sensors in a centralized manner [9].

C. Q.bloxx XL A127

The Q.bloxx XL is a module specifically designed for high-voltage and current measurement applications and electrical power measurements. It is part of the Q.series product family offered by Gantner Instrument. This module has high-performance features and custom sensor terminations, making it ideal for use in widely distributed installations.

The device is equipped with four electrically isolated analog inputs that offer high-accuracy digitalization. It features a 24-bit ADC and a sample rate of 100 kHz per channel. The module has four voltage input channels that can measure configurable ranges up to ±1200 V and two inputs for current measurement via shunt resistors, with configurable ranges up to ±2400 mV. These resistors are used to measure the small voltage drop across them, which is directly proportional to the current flowing through the circuit, thus providing accurate current measurements.

The maximum shunt resistor value is 2.4 ohms, considering the maximum range of voltage drop and the maximum current that comes from DQ640ID-B, which is 1 A. Overall, the Q.bloxx XL is a highly reliable and efficient module that is suitable for various electrical measurement applications [10].

D. Q.station XT Controller

The Q.station XT Controller is a high-performance edge controller that has been optimized for data acquisition tasks. It offers precise synchronization and high-speed redundant data logging, and supports a wide range of communication protocols, including TCP/IP, Modbus, and EtherCAT, which makes it very flexible for various industrial applications.

The Q.station XT can handle a significant amount of data, with the capacity to manage 2048 bytes of data, which equates to 512 variables for both reading and writing operations. It offers impressive data transfer rates, capable of online and block transfers up to 16 MByte/s, and can handle 32 variables at a 100 kHz sample rate.

The Q.station XT is known for its precision, as system synchronization accuracy is maintained at ± 1 μs, ensuring that data collection and control tasks are executed with minimal deviation. This controller is ideal for applications that require high-speed data logging, real-time processing, and synchronization across multiple devices. Its capabilities make it suitable for this project [11].

E. Q.bloxx XL F100

Q.bloxx XL Series is a family of data acquisition modules from Gantner Instruments. that connect to a central data acquisition system and F100 model is an Optical Universal Asynchronous Receiver Transmitter (UART) Extension module designed for high-performance data acquisition systems, offering baud rates up to 1.5 MBaud and optical transmission distances up to 3800 m. this is ideal data acquisition (DAQ) solution for widely distributed installations that require high data acquisition speeds and handling a large number of channels [12].

F. GI.bench

GI.bench is a software program created by Gantner Instruments. It is designed for data acquisition, visualization, and analysis. By connecting the controller to a PC, we can configure all connected modules for various measurement tasks. This includes defining sensor types, setting up channels, and specifying data acquisition parameters like sampling rate and resolution. With GI.bench, we can view real-time data from various sensors and channels simultaneously as the experiment progresses.

TABLE I: Main accelerator's components

Component's categories	Main components	Power range	Characteristics
Synchrotron light generation	Injector PS + Microtron dipole	2 kW	Relatively low power consumption with noticeable variations due to pulsing of electron beam
Superconducting Magnet Systems	CATACT and CLIC wiggler	26 kW	Create a magnetic field pattern for the synchrotron beam. Switching or adjusting fields can cause significant power fluctuations
Steering and Bending Magnets	Dipole, quadrupole and sextuple magnets for booster and storage ring	200-300 kW	Controlling these magnets requires precise current adjustments, which can cause rapid changes in power consumption, particularly during beam tuning and adjustments and magnetization cycling
Radiofrequency (RF) accelerating structures	RF for booster and storage ring and klystron	4 kW*	*: measurable part only. Used to increase the energy of charged particles and compensate radiation losses. Due to variations in beam intensity and energy, their operation can cause rapid and significant fluctuations in power demand.

III. Selection of Optimal Measurement Points

In this section, we will discuss the process of determining the optimal locations for installing voltage and current sensors in the KARA facility, with a focus on the strategic placement of these systems.

To identify the critical points, we conducted a detailed analysis of the energy consumption of the main components of the KARA storage ring. This analysis involved examining the power consumption profiles of key components over the past three years. We established two primary parameters for selecting these components, those with consistently high consumption rates and those exhibiting significant variability and fluctuations in consumption.

After analyzing the data, we have identified 17 main components that fall into five categories, which were considered critical for monitoring due to their substantial

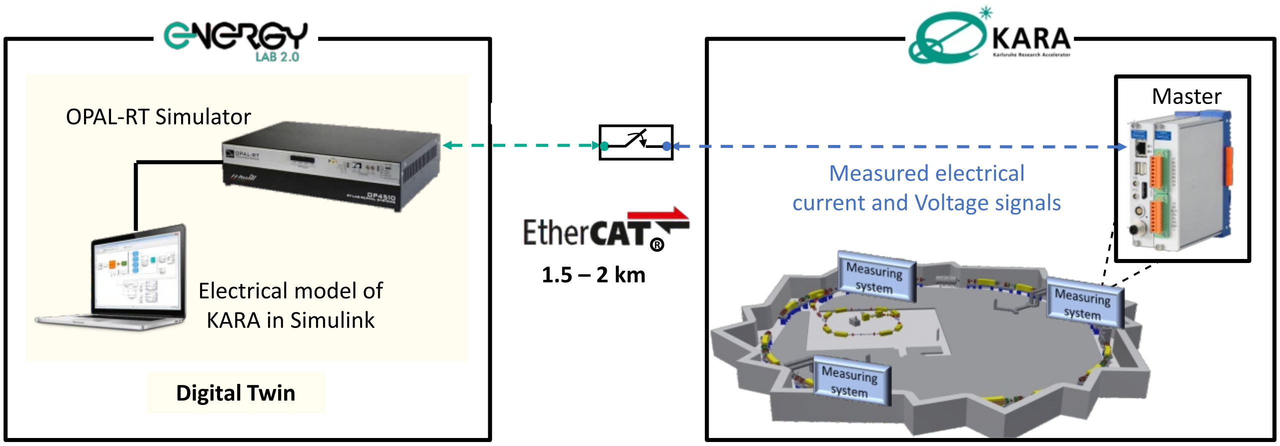

Fig. 2: Communication Infrastructure developed between the accelerator KARA and Energy Lab 2.0 at the Karlsruhe Institute of Technology

energy usage and fluctuating consumption patterns. Please refer to Table I for details.

In order to measure the electrical parameters of these 17 components effectively, we have divided them into seven groups. Each group is assigned to one Gantner master module of measuring systems that is customized to their specific characteristics and operational requirements. This is already shown in Figure 1. Our aim is to ensure comprehensive monitoring coverage during experiments.

IV. Data stream transportation

In this section, we will discuss the detailed process of transmitting data from the KARA facility to the Energy Lab for analysis.

Our measuring system collects voltage and current measurements along with corresponding timestamps, which are securely stored in the Q.station data logger. To ensure that these essential data points reach the Energy Lab promptly, we use optical fibers integrated with industrial communication protocols such as Modbus or Ethercat.

As you can see in Figure 2, for data transmission between the KARA facility and the Energy Lab, the integration of various devices relies on well-designed network architecture. Central to this architecture are the IP addresses assigned to each device, facilitating seamless communication across different network segments. The controller within the KARA facility utilizes a private IP address to connect to the local network, enabling it to interact with other components of the system. Conversely, the OPAL-RT real-time simulator is configured with two different IP addresses. One of these addresses links it to a PC housing a simulated model of KARA, while the other connects it to the broader KIT network, allowing for comprehensive data analysis.

The interface acts as a mediator, facilitating communication between KARA and the Energy Lab by aligning its IP address with the controller at one end and adopting a compatible IP address for the OPAL-RT simulator at the other end. This enables seamless data transfer across different network configurations through optical fiber connections.

During our testing phase, we evaluated the effectiveness of our communication setup using the Modbus protocol. As depicted in Figure 3, the first data package transmitted included the voltage waveform, with a System Cycle of 1 ms and a Sampling rate of 20 kHz.

Modbus is a widely used communication protocol in industrial settings due to its reliability. It streamlines communication between electronic devices by organizing data into registers, making it easier to read and write data between devices [13]. However, the results of the first transmitted data package through Modbus TCP/IP exhibit limitations that prevent its suitability for high-speed real-time data transfer. A key constraint lies in its data packet size. Modbus typically limits data transfer to around 125 registers (holding) per message, translating to roughly 250 bytes after accounting for overhead. This restricts the amount of data transferred per cycle, impacting overall communication speed. Furthermore, the master-slave polling architecture inherent to Modbus introduces delays as the master device queries each slave sequentially. This polling mechanism becomes inefficient for real-time applications with high data rates, where devices require immediate data transmission. These limitations and network overhead associated with TCP/IP communication contribute to Modbus TCP/IP's unsuitability for applications demanding real-time data transfer at 10 kHz ranges [14].

By establishing a data transmission system, we ensure that critical information from the KARA facility is accurately delivered to the digital twin in Energy Lab. However, to enhance our data transmission capabilities, we need to upgrade the communication protocol to Ethercat, a faster and more efficient protocol.

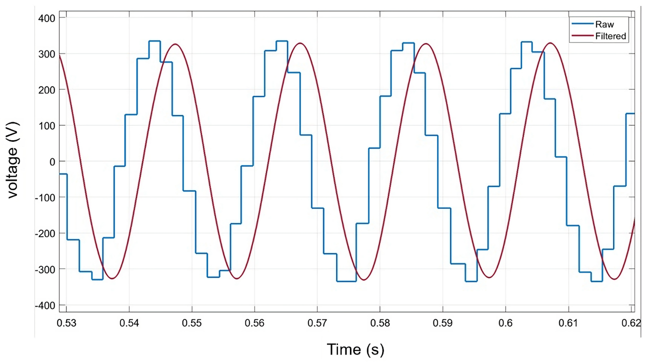

Fig. 3: Transmitted voltage waveform data package by means of Modbus communication at 1 kHz sampling rate

V. Future work

To achieve a data transmission rate of 10 kHz, the current communication protocol (Modbus TCP/IP) must be upgraded to EtherCAT. To ensure compatibility with EtherCAT, the existing communication modules will be assessed, and an extension module may need to be added for the EtherCAT interface.

To facilitate development and testing, a model of the EtherCAT interface and data acquisition process will be created in Simulink. A dedicated EtherCAT network will also need to be established, including direct fiber optic cable installation between KARA and the energy lab. This eliminates the need for intermediary devices and minimizes signal degradation over longer distances.

VI. Conclusion

The experimental setup described in this paper successfully establishes a real-time communication infrastructure between KARA and EL2.0, demonstrating the potential for significant advancements in energy management and power quality within research accelerator facilities. The integration of advanced sensor technology, high-performance data acquisition systems, and the implementation of a digital twin using real-time simulation has proven to be effective in accurately replicating the operational dynamics of the KARA facility. This approach enhances understanding of interactions in the accelerator's power supply system and paves the way for future operational efficiency and sustainability improvements.

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