

# Power system protection and control testing in a fully virtualized environment

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**Abstract**— Factory Acceptance Test (FAT) is a crucial step in the validation of the protection and control system in a power substation or network. To guarantee the conformity and reliability of the protection and control solution prior to its integration in the power network, it is necessary for the FAT to be performed in conditions that are as representative of the reality as possible. This necessity usually involves the deployment of important and costly material and human resources. This paper presents an innovative approach for the implementation of a fully virtualized test platform for testing a protection and control system based on a Siemens solution. This virtualized test platform provides a powerful and flexible virtual environment for performing FAT in realistic conditions, without having to support the various costly constraints associated with physical platforms (equipment’s procurement, assembly, wiring, power supply, ...). Besides the Devices Under Test (Protection Relays and Bay Control Units), the substation’s primary equipment (circuit breakers, disconnectors, etc.) are also modeled and simulated at the virtualized platform level. The virtualized test platform presented in this paper is based on the Siemens Siprotec 5 Digital Twin, which is a real-time digital replica of a physical Siprotec 5 device including interfaces, functions and algorithms. The ease of implementation and use of the Siprotec 5 Digital Twin, combined with the flexibility and power of its features, make it the key element of the virtualized test platform.

**Keywords**— Protection and Control System FAT, Virtualized test platform, Siprotec 5 Digital Twin

## I. INTRODUCTION

Power network digital protection and control schemes are complex decentralized systems, composed of several elements distributed over the entire electric network at power substations and control centers. This decentralization results in significant interactions and data exchanges between the different system’s components, which in turn, usually involves the deployment of important and costly material and human resources to implement the end-to-end testing of the different protection and control functions.

Fig. 1 represents an overview of a typical modern power substation digital protection, automation and control system. The major components that constitute this system can be classified in three distinct categories, according to their hierarchical automation level:

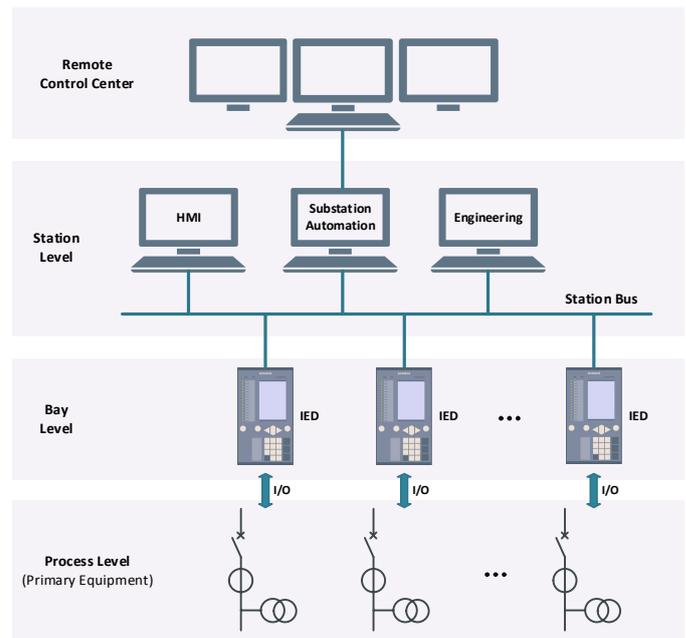


Fig. 1. Substation’s protection, automation and control system

### A. Bay Level

The Intelligent Electronic Devices (IED) located at the bay level represent the key elements of the protection and control scheme. The bay-level IEDs consist mainly of Protection Relays (PR) and Bay Control Units (BCU) which host and process the different protection functions algorithms and control logics. As its name indicates, in terms of functional boundaries, a bay-level IED is usually dedicated to a single substation bay. From the functional testing point of view, the bay-level IEDs constitute the main Devices Under Test (DUT) of the whole protection and control system.

### B. Station Level

The components of the protection and control system located at the station level consist mainly of the Substation Automation System (SAS) and the Human Machine Interface (HMI). The Substation Automation System collects, centralizes and processes the data generated from the different sources

(bay-level IEDs, remote control centers, ...) and transmits them to the appropriate destinations. In particular, the substation remote control and monitoring from the control centers is performed through the SAS. The HMI is used by substation operators to monitor and control the substation locally.

### C. Process Level

The low voltage (LV) circuits of primary equipment located at the process level, constitute the last major components of the protection and control system. Circuit breakers (CB) and disconnecter switches (DS) control drives, as well as secondary circuits of current and voltage transformers (CT/VT) belong to this category.

In order to implement the necessary protection functions algorithms and control logics, the different components represented in Fig. 1 must communicate together. In terms of signals exchange and data communication, we assume that:

- The bay-level IEDs communicate with the station-level equipment through an IEC 61850-8-1 station bus.
- The signals exchange between the bay-level IEDs and the process-level primary equipment is done through conventional hardwired cables including both digital I/Os and CT/VT current and voltage analog signals.
- Data exchange between the different bay-level IEDs can be performed directly through conventional hardwired cables (digital I/Os) as well as through station bus IEC 61850-8-1 GOOSE communication.
- Data communication between the Substation Automation System and the remote control centers is performed according to the IEC 60870-5-104 protocol.

Based on the presentation above, it is obvious that from the functional testing point of view, bay-level IEDs represent the key elements of the protection and control systems: On the one hand, they are the equipment on which the major protection function algorithms and control logics are implemented and on the other hand, they communicate and exchange data with all other system's components. For this reason, as already mentioned, bay-level IEDs constitute the main Devices Under Test (DUT) of the whole protection and control system. Conversely, even though the process-level primary equipment are inseparable components of the whole protection and control system, they are not really considered as DUT from the functional testing point of view.

## II. CONVENTIONAL FAT CONSTRAINTS

Factory Acceptance Test (FAT) is a crucial step in the validation of the protection and control system in a power substation or network. To guarantee the conformity and reliability of the protection and control solution prior to its integration in the power network, it is necessary for the FAT to be performed in conditions that are as representative of the reality as possible. In practical terms it means that during the FAT, we should ideally be able to implement and test the complete protection and control system represented in Fig. 1.

Among the different system components of Fig. 1, the station-level equipment (SAS and HMI) are the easiest to implement during the FAT, as they are generally limited to

software applications installed and running on a couple of standalone personal computers (PC). The remote control center system can also be implemented on a single PC without much effort. On the other hand, the bay-level IEDs are generally mounted and wired in dedicated cubicles and, according to the number of bays, providing, wiring and powering all of them during the FAT, could involve the deployment of important and costly material and human resources. Finally, the process-level primary equipment are generally not available during the protection and control system FAT and providing or modelling them involves in most cases, important and costly material resources [1].

## III. VIRTUALIZED TEST PLATFORM OBJECTIVES

The purpose of this paper is to present a fully virtualized platform architecture in which, the physical components of the protection and control system shown in Fig 1 are replaced by their "virtualized" versions. In order to be functional in a practical point of view, the virtualized platform must fulfill two essential conditions: Its behavior must be identical to that of the real system, and it must be easy to implement. The degree of accuracy of the similarity between the physical equipment and its virtualized version is particularly fundamental for virtualized IEDs, as they constitute the main system's DUT. The fully virtualized platform presented in the following sections, meets both conditions and provides a practical environment to simulate, test and validate a complete protection and control system in practical conditions, while avoiding the physical constraints.

## IV. SIEMENS SIPROTEC 5 DIGITAL TWIN

In modern substation's control and protection scheme based on Siemens solutions, the bay-level IEDs are physically implemented by Siprotec 5 numerical relays. This section presents the Siemens cloud-based Siprotec 5 Digital Twin, as the key element of the virtualized test platform.

### A. General Presentation

The Siemens Siprotec 5 Digital Twin is a real-time digital replica of a physical Siprotec 5 device, generated through a very easy-to-implement virtualization process as pictured in Fig. 2. The so obtained Digital Twin, provides features and behavior identical to the real configured equipment. Moreover, the Digital Twin can replace the real system's physical IED without requiring any additional engineering or manual adaptation. This characteristic is fundamental to guarantee that the simulations and the tests results obtained with the Siprotec 5 Digital Twin are transposable to the physical IED.

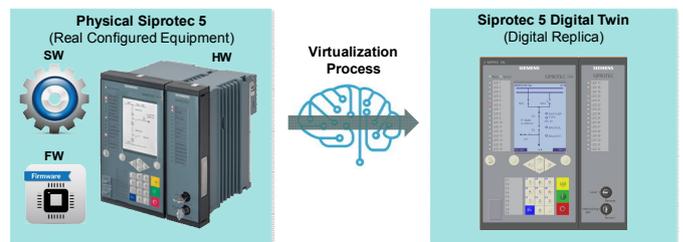


Fig. 2. The Digital Twin is a real-time digital replica of a physical relay

### B. Virtualization Process

Generating a “ready to use” Digital Twin from a real configured Siprotec 5 relay is a straightforward task, achievable in a couple of minutes without additional effort, through five simple steps:

- i. Open the Siprotec 5 configuration tool (DIGSI 5)
- ii. Export the configured relay(s) to a “.sim” file
- iii. Connect to the Cloud (via a secured VPN session)
- iv. Import the “.sim” file
- v. Run the generated Siprotec 5 Digital Twin(s)

Fig. 3 represents a Siprotec 5 Digital Twin running in the cloud-based simulation environment.

### C. Features and Functionalities

The Siprotec 5 Digital Twin behavior is globally identical to that of the original equipment, and particularly regarding the following features and functionalities:

- Operation panel commands and indications (keypads, key switches, display views and menus, LEDs...).
- Protection functions algorithms, control and automation logics, settings, ...
- Communication and online testing and diagnosis with the engineering tool (DIGSI 5).
- Communication with station-level equipment (IEC 61850-8-1 MMS Server).
- Communication with other bay-level IEDs (IEC 61850-8-1 GOOSE).
- Communication through the relay’s protection interface (e.g. for differential protection scheme).
- Web Browser communication for device monitoring (device information, settings, measurements, logs...).

Further to the characteristics inherent to the Digital Twin as mentioned above, the cloud-based simulation environment integrates the following tools and facilities in order to provide additional interactions with the Siprotec 5 Digital Twin through its analog and binary I/Os:

- Setting (forcing) the Digital Twin’s binary inputs.
- Injection of single-phase and three-phase current and voltage sinusoidal signals to the Digital Twin analog inputs. (feature used for simulating the process-level CT/VT secondary currents and voltages).
- Virtual I/O wiring between two or more Siprotec 5 Digital Twins.

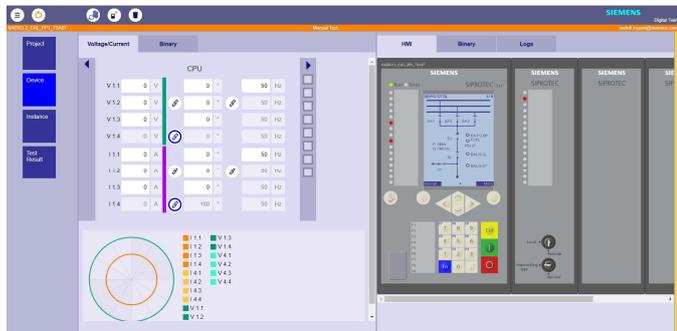


Fig. 3. Siprotec 5 Digital Twin running in the simulation environment

The ease of implementation and use of the Siprotec 5 Digital Twin, combined with the flexibility and power of its features and functionalities, allows to easily and quickly replace any Siprotec 5 IED integrated in a physical system, by its identical Digital Twin.

### V. PRIMARY EQUIPMENT MODELLING AND SIMULATION

As already mentioned, providing or modelling the primary equipment control drives during FAT involves in most cases, important resources in terms of costs and time. Furthermore, as represented in Fig. 4, the binary signals exchange between primary equipment control drives and bay-level IEDs is implemented through hardwired cables. This fact constitutes an additional constraint in terms of FAT implementation.

The Siprotec 5 Digital Twin provides a powerful and flexible way to model and simulate the missing physical primary equipment, with a few efforts. The main idea is to use the Siprotec 5 Digital Twin to model both the physical behavior and the electrical interfaces of the real LV control drive: The physical behavior is modelled by means of the Siprotec 5 Continuous Flow Chart (CFC) logic and the electrical interfaces (i.e. the Open/Close auxiliary contacts) are modelled through the Siprotec 5 binary I/Os.

Fig. 5 represents the communication between a simulated primary equipment and a simulated IED, as implemented in the virtual test platform environment.

The following features are some non-restrictive examples of primary equipment’s physical behaviors modelled with the Siprotec 5 Digital Twin:

- CB tripping / closing orders and open / close positions signaling (unipolar / tripolar).
- CB pole discrepancy.
- DS opening / closing orders and open / close positions signaling.

Modelling and simulating the primary equipment with the Siprotec 5 Digital Twin provides the following benefits:

- The real primary equipment can be easily substituted by their equivalent virtual models to form “virtual bays”.

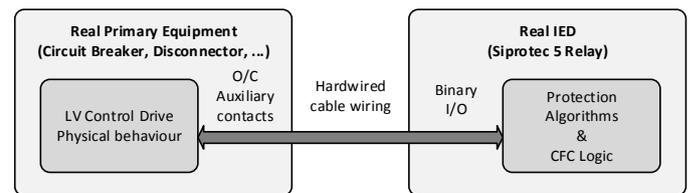


Fig. 4. Communication between real primary equipment and relay

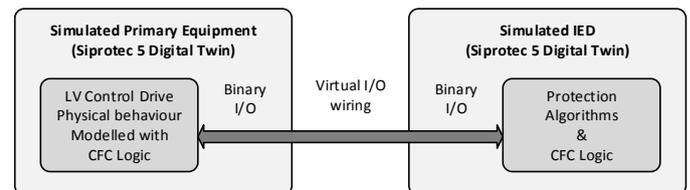


Fig. 5. Communication between simulated primary equipment and relay

- The virtual model can be easily refined or upgraded and is more flexible than the hardware simulators commonly used during conventional FAT.
- The physical cables between primary equipment and the real IED are replaced by strictly identical virtual I/O wiring between two Siprotec 5 Digital Twins. This essential feature results in a Digital Twin with strictly the same binary I/O assignment as the physical relay, so avoiding any potentially time-consuming I/O reassignment in the Digital Twin side.

## VI. FULLY VIRTUALIZED TEST PLATFORM ARCHITECTURE

Based on the elements described above, the physical substation's protection, automation and control system of the Fig. 1 can be virtualized according to the platform architecture represented in Fig. 6. In this fully virtualized test platform:

- The station-level components (i.e. the Sicam PAS SAS, the Sicam SCC HMI and the DIGSI 5 IED configuration tool) are virtualized by installing and running the corresponding software applications on one or several virtual machines.
- Each bay-level physical Siprotec 5 IED is simply replaced by its Digital Twin. This substitution is totally transparent as seen from the system.

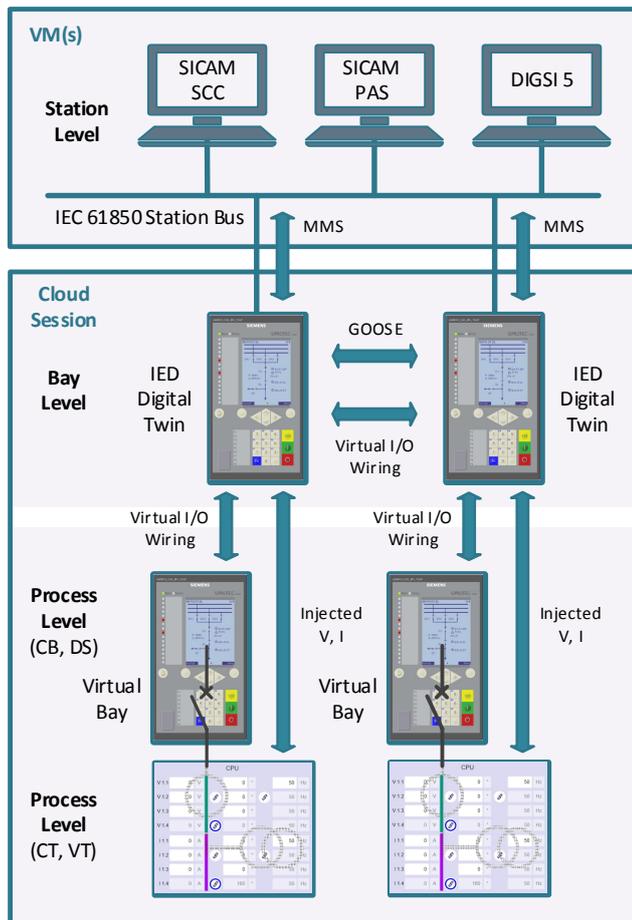


Fig. 6. Fully virtualized test platform architecture

- In terms of network communication, all the IEC 61850 MMS and GOOSE messages configured in the physical system, are automatically published and exchanged between the corresponding virtualized communicants without requiring any additional engineering or manual adaptation.
- The process-level primary equipment are substituted by appropriate Siprotec 5 Digital Twins which model and simulate their behavior and electrical interfaces.
- The signals exchange between the bay-level IEDs and the process-level primary equipment is done through virtual I/O wirings between Digital Twins.
- The CT/VT current and voltage analog signals are generated and injected via the simulation environment.
- The virtual machines and the cloud-based Siprotec 5 simulation session are running on a single PC.
- The remote control centers are not represented in Fig. 6 as the communication between the SAS and the higher automation levels is not the main subject of this paper. However, this communication can also be virtualized with an additional virtual machine.

## VII. FURTHER APPLICATIONS

Although the focus of this paper is on fully virtualized test platforms, the application area of the Siprotec 5 Digital Twin is not limited to the fully virtual schemes, but it covers also the integration in real substation automation systems. In other words, in real protection and control systems, it is possible to replace any physical Siprotec 5 relay by its Digital Twin in a totally transparent way for tests purposes, as far as the concern is limited to the relays' behavior and the communication interfaces as described in section IV.C of this paper.

The "virtual bay" presented in this paper gives only an example of the various abilities offered by the Siprotec 5 Digital Twin in the modelling and simulating domain. As another application, one can imagine modelling and simulating the voltage regulator, the OLTC (On-Load Tap Changer) or any other substation primary equipment.

## VIII. CONCLUSIONS

In this paper, we presented a flexible and powerful virtual environment which allows to perform easily the control and protection system FAT in realistic conditions, without having to support the various costly and time-consuming constraints associated with physical platforms.

In this regard, the Siprotec 5 Digital Twin plays an essential role as the key element of the virtualized test platform implementation. Indeed, besides to being able to stand in for the system's physical IEDs, it offers a powerful and flexible way of modelling and simulating the missing primary equipment in terms of physical behavior and electrical interfaces, with a few efforts.

## REFERENCES

- [1] L. Chen, T. Charton, H. Li, R. Zhang, "Virtual site acceptance test platform for IEC 61850 based substations with multi-vendor bay solutions", *J. Eng.*, 2018, Vol. 2018 Iss. 15, pp. 791-795.