CIGRE-518 **2022 CIGRE Canada Conference & Expo**
Calgary, Alberta, Oct. 31 – Nov. 3, 2022

# Data Transformation from Simulation Environments to Field Applications and Vice Versa

**Hadi Khani[1], Daniyal Qureshi[2], Feng Xu[2], Pankajkumar Sharma[2], Rohan Perera[2]**
**[1]Quanta Technology, Canada**
**[2]Hydro One Networks Inc., Canada**

## SUMMARY

Data transformation can be accomplished in different ways, depending on the application. This paper describes how data can be collected from electric power system simulation platforms, processed, and transformed for field applications. The paper highlights that with the increasing number of advanced simulation platforms and third-party software applications, large amounts of data can be produced for engineers to review and make educated decisions. The authors substantiate their argument by presenting data conversion techniques and simulation platforms used for power system protection analysis and the solutions developed for subsequent data analysis. Simulation data is initially collected from industry-level simulation platforms largely utilized by transmission or distribution electric utilities. Such data is then further processed, considering users' input to produce a technical summary for utility engineers to review and take the necessary actions accordingly (e.g., change relay settings to alleviate inadvertent relay tripping and outages). While the simulation and/or processed data provide valuable information to the utility engineers, they cannot be directly applied to the field area.

This paper develops new techniques for field applications' automated transformation of simulation data. The aim is to fill the gap between the existing functionalities of electric power analysis programs and what the field environment needs for easier implementation. The paper further discusses techniques for transforming data from the field domain to a format suitable for simulation and analysis. The raw data collected from the field can be used for enhanced simulation and analysis for various reasons (e.g., finding the root cause of relay misoperations).

The proposed techniques are tailored for developing test points for relay testing and commissioning purposes in the substations. The paper demonstrates how phasor-domain data collected from the simulation environment can be converted to time-domain signals using formula-based approaches and injected into protective devices for testing and commissioning. The paper shows that not all the details associated with a time-domain signal need to be added to the synthesized signals for relay testing purposes. Rather, only the details relevant to the application should be captured. It is worth noting that for many other applications such as analysis of inverter-based resources, time-domain analysis is still needed, since synthetic time-domain signals can only be used for certain applications. The paper also unveils how data collection from data sources, simulation, processing, and transportation for field applications can be automated for cost savings and to avoid human error.

A major Canadian transmission utility has successfully applied the proposed relay testing and commissioning process in the field, and the utility is currently considering replacing its old procedure.

Simulation and experimental data collected from the lab and field show how the current field procedure for relay testing can be significantly enhanced. A proof-of-concept is made by applying field techniques using industry-standard software and hardware and using the required communication protocols. The field data is collected and analyzed to demonstrate the efficacy and feasibility of the proposed techniques and their practicality for electric power utilities across the globe.

**KEYWORDS**
Data transformation, testing, protection settings, simulation, modeling, field.

## 1 INTRODUCTION

Across numerous industries, the capabilities of advanced software and hardware solutions to aid engineers in the design process are rapidly increasing. This development presents engineers with large amounts of data for device settings, measurements, and studies, which can be reviewed for better decision-making in improving system reliability.

Design engineers can leverage software simulation technologies to model and study the overall system. However, simulation data is constrained to the software environment and disconnected from the tools and processes in the field. With such large amounts of data in such diverse formats, there is a growing need for a data transformation methodology across the simulation and field environments, referred to in this paper as a *simulation and field data bridge*. To devise such a methodology, the limitations of both software and hardware tools must be considered.

## 2 DATA TRANSFORMATION

This paper proposes that effective data transformation from simulation environments to field applications and vice-versa requires a high-level framework similar to that depicted in Figure 1.

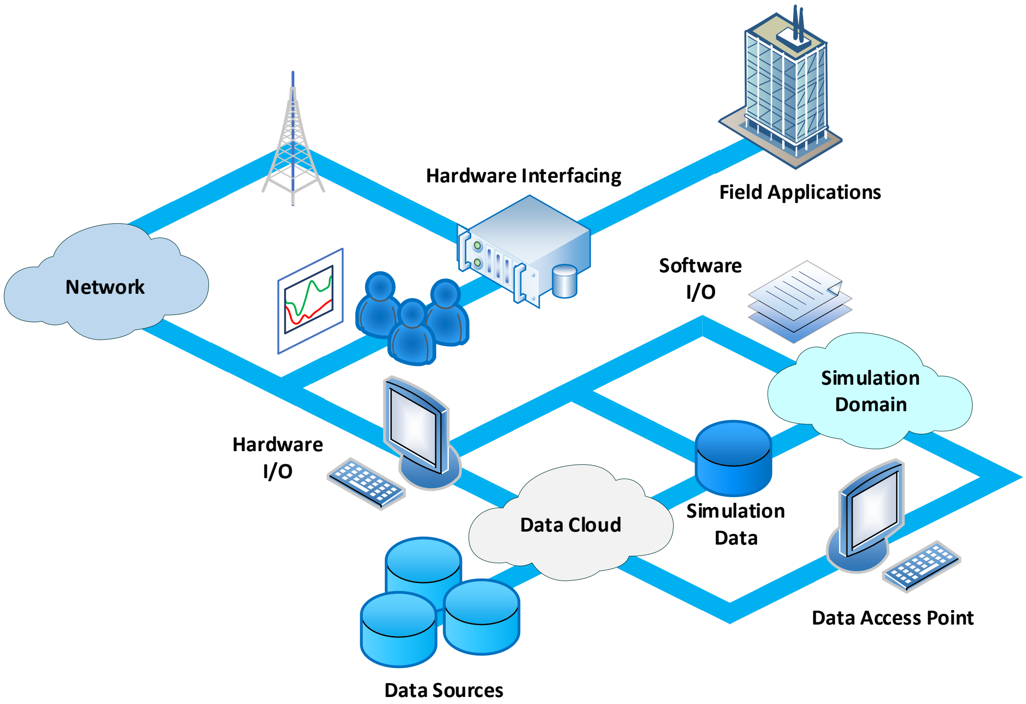


Figure 1. The high-level framework for data transformation from simulation environments to field applications and vice versa.

The various components of Figure 1 are touched upon in Table 1 below.

Table 1. Description of components in the data transformation framework.

| | |
|---|---|
| **Data Sources & Cloud** | All data is hosted on physical servers, which are read/written through network applications over a data cloud. |
| **Simulation Data & Domain** | Data from the cloud necessary for simulations is transferred to a simulation database, which is utilized to build a software model of the system in the simulation domain. |
| **Data Access Point** | An endpoint where an engineer connects to the simulation and field data bridge. |
| **Software I/O** | The engineer interacts with automated tools in the simulation domain to input/output files to the data cloud. |
| **Hardware I/O** | The engineer connects to the physical device to be able to load settings and test cases from the data cloud and monitor functions. |
| **Hardware Interfacing** | The interface of physical devices to their applications in the field. |

The cybersecurity requirement compels some considerations to be undertaken while transforming data across the framework. Other considerations include accounting for phasor-domain (simulation) data limitations versus time-domain (field) data during conversion. These considerations are addressed in the sections below.

## 2.1 Cybersecurity Measures

The increasing cybersecurity requirements invoke an evident challenge to the uninterrupted data flow between different software and hardware environments, particularly in industries overseeing critical infrastructure like the power grid. The cybersecurity approach of the proposed simulation and field data bridge is 1) to minimize critical infrastructure protection data at any stage in the transformation and 2) to control access at all data access points connected to the bridge in both the simulation and field environment.

Before insertion into the simulation domain, data must be classified according to its cybersecurity risk. The simulation database only requires information necessary for the software model to mimic system operation and device functionalities. The tool used to automate the modeling of the database is configured to extract this data and exclude remaining settings from entering the simulation domain. Data access points are password-restricted and accessible only on a private network with encryption.

## 2.2 Time-Domain vs. Phasor-Domain

It might be difficult to model and simulate time-domain data in software for large-scale applications such as a utility power transmission network with hundreds of elements. At each time step in a time-domain simulation, the instantaneous values of quantities for all elements in the network must be recalculated, consequently requiring substantial computer processing time and power. Since multiple simulations must be performed in the design process to account for system contingencies, scheduling and budget constraints could restrict this approach.

The existing alternative employed by utilities is a phasor-domain simulation of the network. In the phasor domain, signals are treated as steady-state magnitudes and angles. They are calculated once, reducing the time required for simulation. Steady-state phasor analysis ignores the transient response and the evolving nature of events like power system faults. It is generally accepted that phasor-domain simulations are adequate for the design stage with the incorporation of tolerances in the process.

However, real-life hardware inputs/outputs will be processing time-domain data in the field. In order to better replicate the behaviour of the devices under test, test units must feed synchronized time-domain signals into devices. A steady-state time-domain signal interval can be synthesized from a phasor, but it is challenging to edit this signal to provide a more realistic waveform for relay testing. It is proposed that only certain key items must be added to this time-domain signal to accommodate the field's testing requirements [1]. For instance, in the case of power system protection, the effect of a decaying DC component in a fault can be artificially appended to the early stages of the event. For faults relevant to transformer protection, the relay functions to prevent tripping for inrush current must be evaluated. Inrush currents can be identified through multiple harmonics in the current signal. However, the second harmonic generally comprises the highest content. Thus, it is proposed that only a percentage of the second harmonic needs to be artificially imposed on the generated time-domain signal to verify that the relay's inrush current detection functionalities will work at the testing stage. It is worth noting that the use of second harmonic approach for blocking the transformer differential protection during transformer energization may not work for all transformers, and thus, alternative approaches need to be adopted.

## 3 POWER SYSTEM PROTECTION APPLICATION

The concepts discussed in this paper have been applied to a real-world, large-scale power system network model. Figure 2 represents the bridge's role in the protection system context.

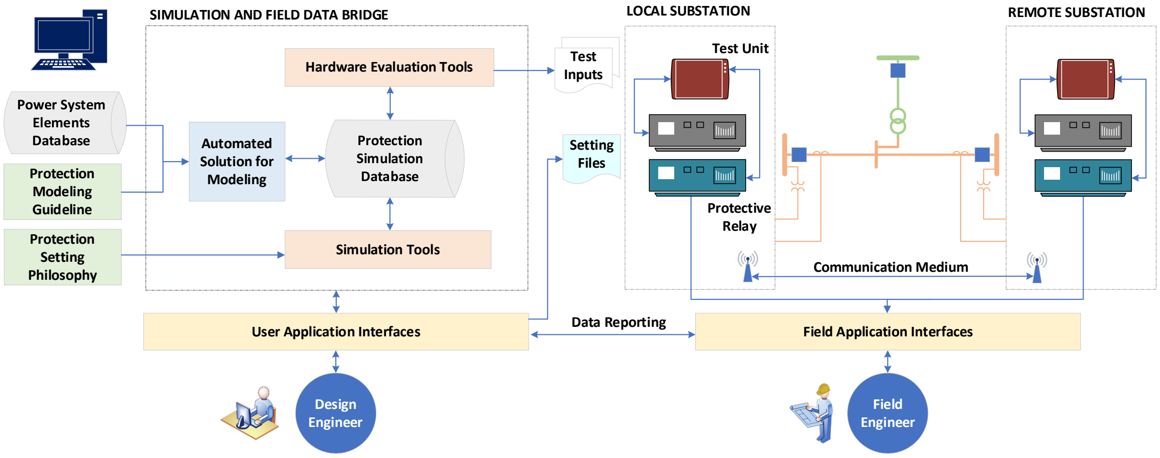


Figure 2. The detailed flowchart of the proposed method for data transformation from simulation environments to field applications and vice versa in the context of power systems and protection.

The following sections detail the components of the simulation and field data bridge in the simulation and the field application domains.

## 4 SIMULATION DOMAIN

Power utilities maintain databases of in-service primary network equipment, as well as protective relay setting files and commissioning/operation documentation. The utility should establish a protection modeling guideline determining the rules and processes associated with representing the primary equipment and relay settings in a database for simulating protection.

The initial task of the proposed bridge in this paper is to facilitate the accurate and efficient conversion of data records into the database for software simulation. This conversion is achieved through an automated solution for modeling, which connects to the power system database and settings repository. It builds and updates the protection system model (relays, current/voltage transformers) required to perform simulations within the software environment. When this automated solution is configured based on the protection modeling guideline, it reduces the time and cost for maintaining the protection simulation database and the risk of manual errors.

Simulation tools provide the design engineer with an avenue for devising and evaluating relay settings in an automated fashion within the simulation environment. They should be configured to reflect the protection setting philosophy developed by the utility. To ensure the overall reliability of the protection system, independent tools are incorporated to study relay selectivity and sensitivity [2].

Through controlling the tools through user application interfaces, the design engineer will use technical summaries from these studies to prevent design errors and revise the settings to minimize the risk of relay misoperation and unnecessary customer blackouts.

## 5 FIELD DOMAIN

In addition to simulation tools, hardware evaluation tools connect to the simulation environment as it saves current and voltage signals from fault simulations chosen to evaluate the specified relay settings. Relay test inputs are created and can be played back into relay test units in the field. Confirming that the physical device will not misoperate is critical. The NERC Protection System Misoperations Task Force identified that 28% of all protection misoperations across the NERC ranging from January 2012 to April 2013 stemmed from incorrect settings [3].

Field engineers monitor the physical protection system through field application interfaces which can facilitate the commissioning of relay settings and test input playback. Test data reporting is carried out between the field and design engineer applications through these interfaces.

The proposed tool for the generation of hardware test set-ready inputs is referred to in this paper as the *test input generation tool*. Accurate fault current and voltage waveforms, containing phenomena such as decaying DC components and the influence of mutual coupling, can be generated within the simulation environment and exported to digital file formats. These files may be played back by test sets in the field. The test input generation tool is a script in the simulation environment that determines the critical set of fault simulations to verify a relay's operation, generates test input files, and saves them according to a logical naming convention [1].

In the past, certain hardware test procedures relied on test points generated by spreadsheets that compute points reflecting general operational scenarios, such as expected fault current/voltage phasors to commission protective relays. These spreadsheets, however, rely on the device's setting file parameters. As a result, they might not detect issues with the settings themselves, thereby limiting the scope of testing to validation of the device's logic.

These factors require computations performed on a complete network model and are present at the simulation stage. Within the bridge, a test point generation tool is developed to extract more appropriate test points from the simulation domain based on the system topology rather than device settings. Figure 3 shows the proposed test cycle incorporating a test point generation tool from the simulation bridge.

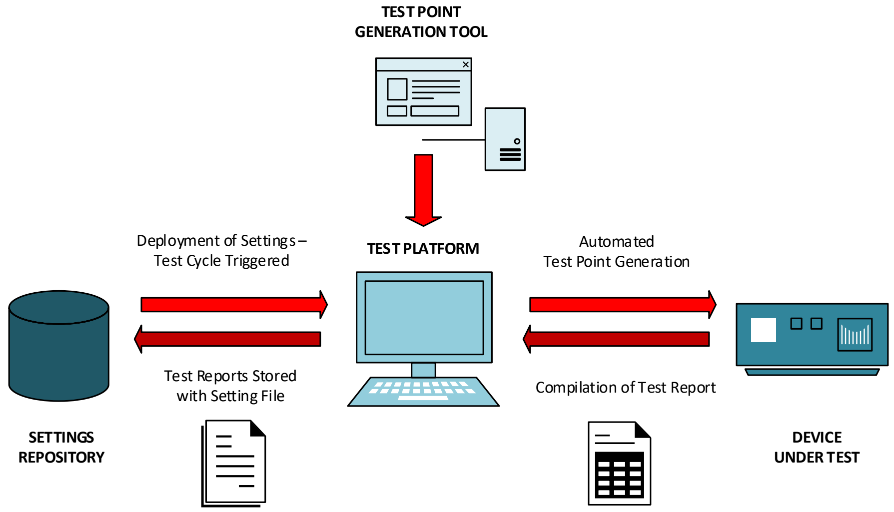


Figure 3. Test cycle interactions incorporating a test point generation tool from the simulation bridge.

The test cycle is initiated when a new setting file for a device is deployed and stored in the relay settings repository. Field engineers then use the test point generation tool on their test platforms for the automated generation of test points using simulations. These test points are evaluated on the physical device under test, and the test reports are compiled. The test reports are returned to the settings repository with the new setting file to complete the test cycle.

## 6 RESULTS AND ANALYSIS

Applying the simulation and field application bridge methodology has proven to successfully detect issues that impact protection system reliability. The following paragraphs describe two real-world examples demonstrating the benefits of incorporating simulation-based test points in the hardware test cycle.

In the first example, line protective relays misoperated for a single-phase-to-ground fault on an adjacent line, as shown in Figure 4. The relays used a directional comparison blocking (DCB) scheme. At Relay 1, the 50N neutral overcurrent element for supervision of the blocking signal was set to 0.1-p.u. per the utility protection philosophy (320 Amps). When a ground fault occurred behind the relay, the fault current was limited to 161.1 Amps, below the pickup setting of the overcurrent element. As a result, the overcurrent element did not trigger a blocking signal, and the remote line end Relay 2 tripped as per the DCB logic.

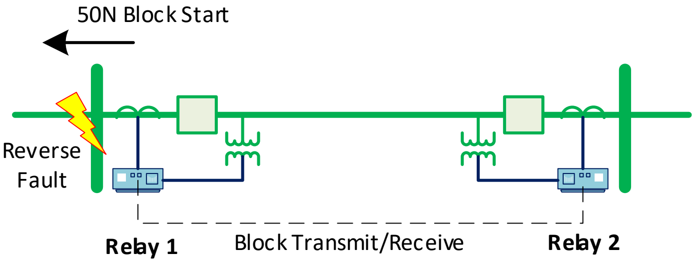
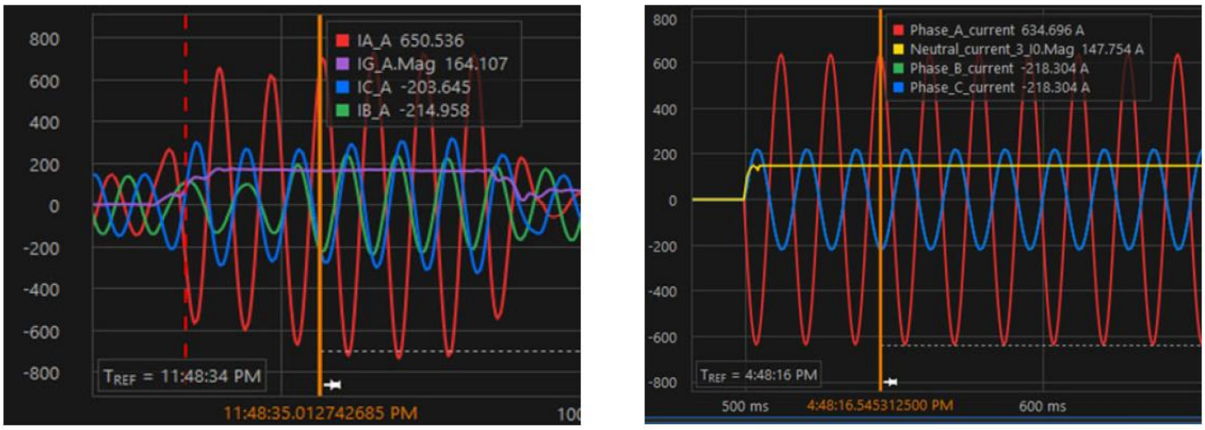


Figure 4. Misoperation of the line protection for a fault on an adjacent transmission line.

The fault was evaluated in the proposed simulation platform and used to generate test points for the field. The resulting automatically-generated test signal is shown in Figure 5, next to the actual event record data from the relay. It is seen that the two signals are highly similar. When playing back these simulation-based test points to Relay 1, the relay misoperated in the same way it had during the real-world event.



(a) Actual event record data from Relay 1.

(b) Test points generated from the simulation bridge.

Figure 5. Comparison of actual event record data vs. generated test points from the simulation bridge.

In the second example, a single-phase-to-ground fault occurred outside a distribution transformer's protection zone. The current differential protection of the transformer misoperated for this fault due to the differential current not totaling zero. An incorrect value had been entered for one of the winding voltages in the relay settings. Thus, the current measurement was multiplied by an inaccurate factor during normalization. Test points were generated from the simulation domain to be played back to the relay, which behaved the same way as in the real world.

Both cases exemplify the effectiveness of bridging the simulation and field domains for relay testing and commissioning as more accurate values stemming from the system topology/phenomena can be used to test hardware. If the proposed process had been applied, both settings issues could have been detected in the test cycle and could have been addressed to prevent the misoperations.

## 7 FUTURE ROADMAP

As additional software and hardware tools are integrated into the data bridge, the process will need a "common language" to ensure minimal data loss and efficient data format translation. Future development of the simulation and field data bridge will necessitate the design of common data transfer protocols.

Analogously, in the context of power system protection, the IEC 61850 standard defines a coherent mapping for communication between physical devices at substations. Similarly, automated software tools within the proposed bridge can avail themselves of a protocol to communicate uniformly with one another and the hardware environment.

## 8 CONCLUSION

The authors of this paper identify the benefits of the simulation domain and testing of hardware in the field domain, as well as the gap between the two domains. The paper introduces data collection, processing, and transformation techniques to reconcile that gap. A simulation-to-field data bridge is proposed, comprised of automated tools and processes intended to facilitate data transformation from simulation environments to field applications and vice versa. The bridge is applied to a real-world power system for protective relay testing and commissioning. The use of automation in the data conversion processes reduces costs and improves accuracy. It is found that the tools and processes are successful at detecting issues and increasing the protection system reliability. The authors recommend future work on developing a software and hardware protocol within the bridge to further improve data transfer efficiency. The field data bridge simulation proves to be an exciting means through which power utilities can unify advancing technologies in the simulation and field for a more reliable grid.

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