Testing Microprocessor-Based Relay Protection: Conventional Devices vs Hardware-in-the-Loop

Student paper

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Abstract—**This article discusses the methods of testing microprocessor relay protection systems, emphasizing the importance of ensuring reliability and security in energy networks. The main focus is on comparing two approaches: traditional methods using conventional devices and modern methods of testing using Hardware-in-Loop (HIL). Traditional methods are simple and intuitive, but have limitations in scalability and security. On the contrary, testing with HIL provides flexibility and the ability to simulate complex scenarios without the risk associated with high currents and voltages. The paper analyzes the advantages and disadvantages of each method, which makes it possible to make more informed decisions to improve the efficiency and safety of relay protection in energy systems.**

Keywords: Power Systems, Relay Protection, Hardware-in-the-Loop, Testing

I. Introduction

In the modern energy industry, the issues of reliability and efficiency of microprocessor-based relay protection systems are becoming particularly relevant [1]. Microprocessor relays have revolutionized protection systems by providing increased speed, accuracy, and adaptability. However, careful testing is required to ensure their correct functionality, which is crucial to ensure reliability and performance. Traditional test methods face a number of limitations related to the variability of operating conditions and the complexity of modeling real-world fault scenarios [2].

This article compares traditional testing devices with HIL method.

II. Overview of Testing Approaches

This section provides an overview of two predominant testing methodologies: conventional testing devices and Hardware-in-the-Loop (HIL) simulation.

Conventional testing methods rely on physical test equipment that injects signals directly into the relay under test to simulate fault conditions. Figure 1 shows the traditional approach to relay testing.

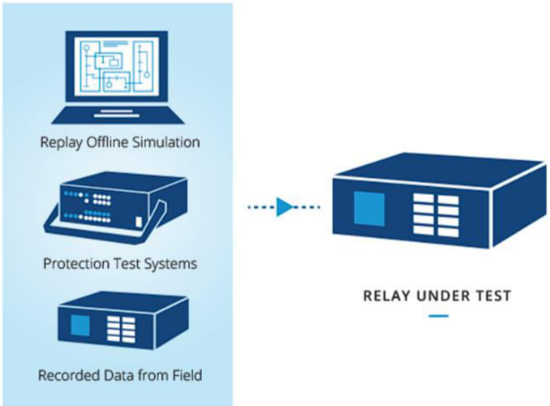

Fig 1. The traditional approach to relay testing [9]

This equipment can generate current and voltage signals that mimic those that would occur during various fault scenarios in a power system. The key advantage of this approach is its directness and simplicity. The relay is tested under conditions that closely resemble its operational environment. However, conventional testing has its limitations. It often requires the relay to be isolated from the actual network or placed into a test mode, potentially disrupting normal operations.

On the other hand, Hardware-in-the-Loop (HIL) testing represents a more advanced and flexible approach [3]. HIL integrates real-time simulation of power systems and actual hardware components, creating a dynamic testing environment where complex and variable network scenarios can be emulated with high fidelity. Figure 2 shows an approach to testing hardware in a loop.

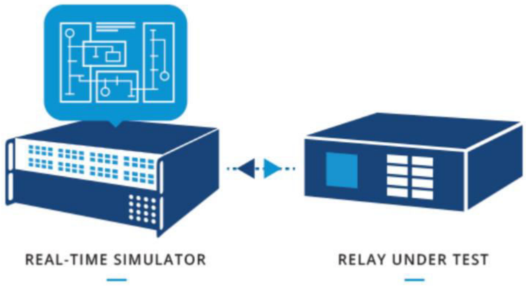

Fig 2. Hardware-in-the-Loop Testing Approach [9]

In an HIL setup, a model of the power system is run in real-time on a simulator, and the microprocessor-based relay is connected to this simulator.

III. Conventional Testing Devices

Testing microprocessor-based relay protection systems is an important practice to ensure the reliability and security of power distribution networks. It includes the simulation of emergency situations to check the correct operation of the protection devices. This section provides an overview and comparison of the characteristics of frequently used devices: Freja-300, F6150 Doble and Omicron CMC.

Freja-300

The Freja-300/306 is one of the most advanced in the line of installations for testing microprocessor relay protection systems. It is a multifunctional tester designed for testing relay protections, automation, and measuring transducers in the electric power industry [5]. The device is shown in Figure 3.

Fig 3. Freja-300 Relay Protection Testing Device

The Freja 300 is capable of simulating a wide range of electrical conditions, including AC and DC voltage generation, currents, as well as simulating various signals and transients, which is critical for testing relay protection. This functionality makes it possible to accurately identify deficiencies and confirm the correct operation of the system.

Freja 300 is equipped with embedded software that allows the user to generate test scenarios, including automated testing, which significantly speeds up the verification process and reduces the likelihood of human error [2].

An important feature is the support of time synchronization with GPS, which allows for coordinated tests over a wide network, important for systems with a distributed architecture. Compact size, lightness, ease of transportation and high efficiency make the Freja 300 an indispensable tool for specialists in the field of electric power industry.

The Freja-300 has the ability to function both with and without a PC connection [2]. After activating the Local mode, it is able to operate independently of the PC. Low-level analog inputs with high accuracy (usually 0.01%) are designed to detect converter outputs. The high-level inputs can be used as a regular ammeter and ohmmeter. The FREJA-300 is capable of generating the following voltage and current values: 4 different voltage values of 150 V (82 VA) and 3 current values of 15 A (87 VA), or 1 current value of 45 A (250 VA), or using an additional external amplification device – 6 different current levels (Freja-306) [5].

The Freja-300/306 system provides flexibility in testing by allowing each output to be changed independently. This device is capable of performing both static and dynamic tests in various modes, including pre-fault testing and damage generation by simultaneously changing parameters and waveforms. The Freja-300/306 can also be used to simulate malfunctions, create and generate interference, as well as to import real interference data, including EMT or COMTRADE files, and edit them using special Freja Sim software.

To perform end-to-end testing, Freja systems at various substations can be synchronized using multiple Freja 306s, allowing an integrated DC power supply to provide relay protection.

F6150 Doble

Another device for testing microprocessor relay protection is the F6150 DOBLE (Figure 4). It is a relay protection testing device designed to test and configure microprocessor protection relays [6].

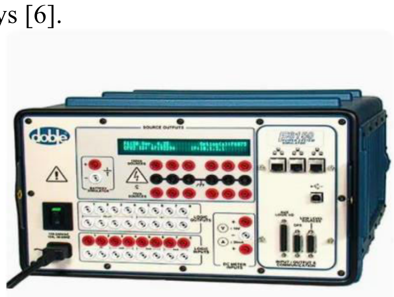

Fig 4. F6150 Doble Relay Protection Testing Device

Equipped with digital signal processing, this device is capable of generating high-precision test signals, which allows you to simulate a wide range of electrical network conditions and test various types of protections. Important characteristics are its ability to simultaneously output up to six current phases (each up to 35 A) and four voltage phases (each up to 130 V), thus providing the ability to test both simple and complex multiphase relay systems.

The device supports the simulation of transient signals, including bursts and harmonics, allowing you to test the functionality of relay protection in various emergency situations. In addition, the F6150 is capable of generating and recording consumer load profiles and system responses to them, which makes it an invaluable tool for developing and testing protection algorithms. The built-in software and user interface make it easy to configure the test parameters, while external communication ports (including USB, Ethernet) make it easier to integrate the device into existing systems and exchange data with a PC.

Main Features [6]:

1. Two-channel testing: The device allows simultaneous testing of two relays, which increases the efficiency of the process.
2. Support for various types of relays: The F6150 Double is compatible with various types of relay protection, including voltage protection and other types of protection.
3. Flexibility in settings: Users can adjust the test parameters according to the requirements of a particular relay.
4. Intuitive interface: The device is often equipped with an easy-to-use interface, which facilitates the testing and configuration process.
5. Test automation: The ability to automate the testing process, which reduces the likelihood of errors and improves the accuracy of the results.
6. Reporting: The device usually provides the ability to generate test reports, which is important for documenting results and meeting standards.

The device also supports advanced analysis of test results, providing detailed data on the operation and effectiveness of relay protection. This includes capabilities to check the response time, sensitivity, and logic functions of the protections. It can be used to implement complex test scenarios, which makes it an indispensable tool for configuring and verifying the safety systems of energy facilities.

The main advantages include the following: improving the reliability of energy systems through regular testing of relay protection. It is also important to reduce equipment downtime due to fast and efficient testing. Another outstanding feature is its flexibility in working with various communication standards and protocols, which makes it possible to effectively integrate it into modern control and automation systems of electrical networks.

Summary

Thus, to summarize, we can conclude that the Freja-300 and F6150 are more focused on automation and graphical representation of data. The F6150 Doble offers the possibility of simultaneous testing of two devices, which may be more effective in certain conditions. All two devices have an intuitive interface, but the Freja-300 can offer a more modern graphical representation. Each hardware also provides reporting capabilities, but the Freja-300 may have more advanced analysis features.

In general, the choice between Freja-300 and F6150 Double,eltn depends on the specific requirements, operating conditions and functional preferences determined by the provisions of the technical environment.

IV. PRACTICAL TESTING WITH CONVENTIONAL DEVICE

To check the relay, the Frey-300 system is used, which is connected to the relay via a voltage and current source. The system is shown in Figure 6 and allows you to check various protective functions of the relay by applying different voltages, current values, phases, frequencies, harmonics.

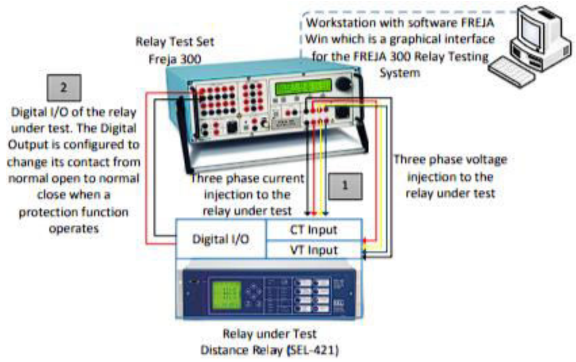

Fig 6. Hardwired Standalone Relay Testing Using Freja-300

Together with the Freja Win software, it is used to connect to the SEL-421 relay and check its instantaneous shutdown function in case of overcurrent [2].

The instantaneous overcurrent protection function is triggered immediately when an excess of the set current level is detected, sending a command to turn off the switch. Such relays are often placed near power sources, as even small delays can cause serious damage to the equipment.

During the test [2], a three-phase current of 1 ampere (RMS) is applied for the first two seconds. Then, at time t = 2 seconds, the current increases to 4.74 amperes. The relay interprets this increase as a short circuit and generates a trip signal. The output contact of the relay changes from normally open to normally closed, which is registered by the Freja-300 system. The entire process takes 8.3 milliseconds, including overload detection (5 ms) and output pin switching (3.3 ms).

Thus, the SEL-421 relay has successfully passed the instantaneous overcurrent protection test.

V. HARDWARE-IN-THE-LOOP (HIL) TESTING

Hardware-in-the-Loop (HIL) testing is a widespread method of testing and verifying the functionality of complex electronic systems or products. It involves integrating the hardware components with which the product or system will interact in the final application, and simulating their behavior in a controlled and repeatable environment. The purpose of HIL testing is to identify and fix problems with a product or system before it is deployed in the intended application, thereby reducing the risk of failure and ensuring compliance with end—user requirements [3]. In HIL modeling, the physical object is replaced by an exactly equivalent computer model operating in real time on a simulator appropriately equipped with inputs and outputs (I/O) capable of interacting with control systems and other equipment. Thus, the HIL simulator can accurately reproduce an object and its dynamics, as well as sensors and actuators, providing comprehensive closed-loop testing without the need for testing on real systems.

To test relay protection systems of electric power systems, various software and hardware complexes are used today, differing in the features of operating modes and other indicators. For a comparative analysis, we will consider such complexes as OPAL-RT, RTDS and Typhoon HILL.

Opal-RT Real Time Simulator

The Opal-RT simulator platform offers innovative solutions for testing relay protection in real time, which significantly improves the quality and reliability of these systems (Figure 7) [4].

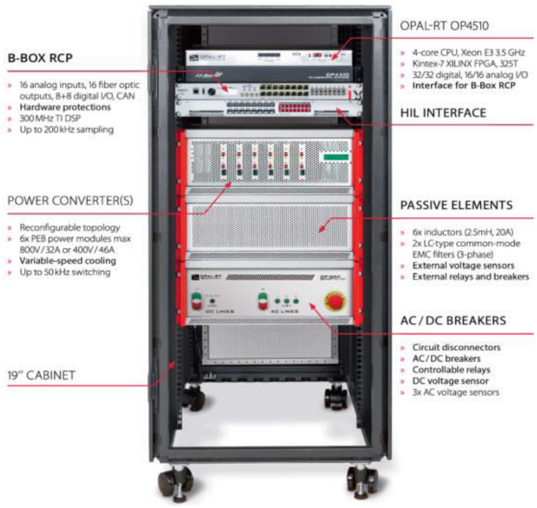

Fig 7. The stand for modeling the Opal-Rt platform

Using powerful computing resources and specialized software, Opal-RT provides an opportunity to simulate the behavior of electrical networks and protection systems in various scenarios [9]. One of the main advantages of the Opal-RT platform is the possibility of real-time simulation. This allows testing relay protection in conditions as close as possible to real ones, which ensures high accuracy of the results. Engineers can monitor the relay's response to various impacts and scenarios, which helps identify potential problems in the early stages of development. Opal-RT supports integration with various devices and systems, including protection relays, current and voltage transformers, and control systems. This allows you to test not only the software, but also the interaction with the real components of the system, which significantly increases the reliability of the results. The platform provides users with the opportunity to develop their own models and algorithms for testing relay protection. Opal-RT supports many standards and protocols used in relay protection, such as IEC 61850 and DNP3 [4]. This allows the platform to be integrated into existing systems and facilitates the testing process.

Using Opal-RT, you can test various protection algorithms used in relays. Opal-Rt offers high performance, it uses standard commercially available processors (for example, Intel Xeon), which may limit its capabilities in some specific scenarios compared to other platforms, such as RTDS and Typhoon HIL. Opal-RT is often fast enough for most applications [9]. This includes checking the timing of the response, sensitivity to various types of faults, and resistance to interference. The platform allows to simulate various emergency situations, such as short circuits, overloads and line breaks. This makes it possible to evaluate the effectiveness of relay protection in critical conditions and identify weaknesses in the system.

RTDS Real Time Simulation

Unlike the Opal-RT platform, the RTDS (Real Time Digital Simulator) [7] platform is more productive and processes data faster (Figure 8).

Fig 8. The stand for modeling the RTDS platform

It provides very high performance and minimal delays due to the use of specialized processors and architecture. This makes it ideal for working with high-frequency signals and critical applications requiring maximum accuracy and speed. A distinctive feature of the complex is that it generates electrical signals (currents and voltages) occurring in the simulated electrical system in physical form in the form of voltages with an amplitude of 10 V.

The RTDS simulator shows excellent performance [8]. It has been actively used for the last 10-15 years [4]. The RTDS environment was created to solve the problems of protecting ultra-high voltage power systems. Later, RTDS was improved to test the safety and stability of control systems. The effectiveness of protection algorithms has been confirmed when used in centralized protection and management systems [4].

Testing of microprocessor relay protection using RTDS includes several steps:

1. System Modeling: Engineers create a model of an electrical system, including all components such as transformers, transmission lines, and protective devices.
2. Setting relay protection parameters: The parameters of the microprocessor relay, such as trip thresholds and time delays, are set.
3. Starting the simulation: A simulation is launched, during which various scenarios of the system operation are created, including normal conditions and emergency situations.
4. Results analysis: After the simulation is completed, the results are analyzed to evaluate the effectiveness of the relay protection. This may include checking the response time, the correctness of relay actions, and other critical parameters.
5. Adjustment and retesting: Based on the data obtained, changes can be made to the relay settings or the system model, after which the testing is repeated to achieve optimal results.

The RTDS platform is a powerful tool for testing microprocessor relay protection, allowing engineers to conduct research and testing in conditions as close as possible to real ones. With its help, the reliability and safety of electrical systems can be significantly improved.

Typhoon HILL Real Time Simulation

The Typhoon HILL platform allows you to simulate real-world operating conditions of power systems and test equipment without having to connect to a real network (Figure 9).

Fig 9. The stand for modeling the Typhoon HIL platform

This is especially useful when developing new devices, configuring them, and verifying the correctness of security algorithms [4].

The main stages of testing microprocessor relay protection using Typhoon HIL:

1. Creation of an energy system model

First, you need to create a model of the electrical system in which the relay protection device will operate. Typhoon HIL has the ability to create complex circuits of electrical networks, including power lines, transformers, generators and other elements. These models can include various operating modes, such as normal operating conditions, emergency situations (such as short circuits), and transients.

2. Setting the parameters of the relay protection device

After creating the power system model, you need to configure the parameters of the relay protection device itself. This includes selecting relay types, trip settings, time delays, and other characteristics that will affect the device's operation under various conditions.

3. Conducting tests

At this stage, tests are conducted that simulate various scenarios of the power system. For example, you can simulate a short circuit on one of the transmission lines and check whether the protection is working correctly by disconnecting the damaged line from the mains. You can also check the device's response to load changes, voltage fluctuations, and other factors.

4. Analysis of the results

After the tests, the results are analyzed. In Typhoon HIL, you can visualize graphs of changes in currents, voltages, and other parameters to evaluate the correct operation of the relay protection device. If errors or inconsistencies are found, you can make changes to the device settings or the power system model and repeat the testing.

5. Documentation and reporting

Upon completion of the testing, a test report is compiled. It indicates which tests have been performed, what results have been obtained, and what conclusions have been drawn. The report can be used to certify a relay protection device or to make changes to a project.

Using the Typhoon HIL [10] platform significantly speeds up the process of developing and testing microprocessor relay protection devices, ensuring high accuracy and reliability of the results.

Summary

Opal-RT stands out for its ability to perform high-performance modeling of complex systems in real time, and is focused on the automotive, aerospace, and energy industries. It is used to test control and protection systems. RTDS, designed primarily for the electric power industry, is particularly appreciated for the accuracy of modeling electrical networks and substations in real time, allowing engineers to test relay protection and automation. Comparative characteristics are shown in Table 1.

TABLE 1
comparison of platform characteristics

Characteristic	Opal-RT	Typhoon HIL	RTDS
Real-time simulation	Yes	Yes	Yes
Modeling flexibility	High	Average	High
Integration with MATLAB/Simulink	Yes	Limited	No
Specialization in energy systems	No	Yes	Yes
Intuitive interface	Average	High	Average
Support for various protocols	Yes	Yes	Yes

VI. Practical Hadware Testing

The OPAL-RT platform is widely used for conducting tests using HIL (Hardware-in-the-Loop) technology. For example, to check the operation of the transformer protection relay. An approximate configuration is shown in Figure 10.

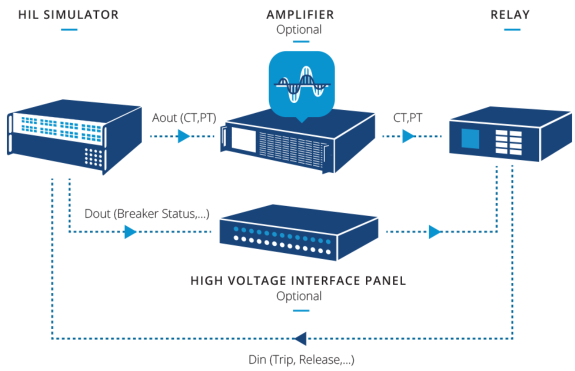

Fig 10. OPAL-RT HIL Configurations for Power System Protection [9]

The main purpose is to check the correct operation of the transformer's differential protection in the event of an internal malfunction. The main relay component is: a real physical relay (relay type Siemens SIPROTEC or ABB REF542plus). The OPAL platform includes the following elements:

- Real-time simulation module (for example, OP4500).
- I/O interfaces (I/O cards) for connecting analog signals from a simulated power source and a physical relay.
- eMEGAsim software for developing models of electrical networks

The fiber-optic connection enables the transmission of analog and digital signals between the network model and the physical relay. A model of an electrical system is being created, including a transformer, a transmission line, and a power source. This is a 110 kV three-phase network connected to a 110/10 kV transformer with a capacity of 50 MVA.

Parameters:

- Primary winding voltage: 110 kV
- Secondary winding voltage: 10 kV
- Transformer power: 50 MVA
- Short circuit current: 8 kA

The model will include various load and short circuit scenarios to test the operation of the relay under various operating conditions. To set up the OPAL-RT simulator, you must:

1. I/O card configuration:

Configuration of inputs and outputs for receiving current and voltage signals from simulated sources and sending relay control commands.

2. Logic Programming:

Creating a script that simulates various network operating conditions, such as normal operation, overload, short circuit inside the transformer, etc.

3. Connecting Relays:

Connecting a physical relay via the interface to the OPAL-RT board.

The model starts in normal operation mode. The measured values of current and voltage are transmitted to the relay. It is necessary to make sure that the relay does not operate incorrectly in the absence of malfunctions. Simulation of a situation when the load exceeds the permissible limits. It is important to check that the relay is working correctly and disconnects the load before the equipment is damaged. Creating scenarios of an internal short circuit in a transformer is one of the key tests, since this is exactly the situation that should lead to the correct operation of the differential protection.

VII. Conclusions and Future Directions

Hardware-in-the-Loop testing represents a significant advancement in the evaluation of microprocessor-based relay protection systems. By combining real hardware with simulated environments, HIL testing offers a comprehensive, safe, and cost-effective approach to ensuring the reliability and effectiveness of relay protection devices. As power systems continue to evolve, HIL testing will play an increasingly vital role in maintaining their integrity and safety [2].

Conventional testing devices play a crucial role in quality assurance and control across various industries. While modern testing technologies have introduced more automation and precision, conventional devices remain valuable due to their simplicity, cost-effectiveness, and ease of use. They are especially useful in environments where high-tech solutions may not be feasible or necessary. The characteristics of Conventional methods and Hardware-in-the-Loop are given in table 2.

TABLE 2
Characteristics of testing methods

Aspect	HIL Testing	Conventional Devices
Testing Environment	Fully simulated	Typically secondary injection or live testing
Grid Impact	No disruption	No disruption for secondary testing; minimal for live testing
Scope of Simulation	Entire power system and protection logic	Focused on relay response to injected signals
Safety	Completely safe and isolated	Safe but requires proper isolation during setup

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