Testing Line Distance Relays During Their Life Cycle

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TESTING LINE DISTANCE RELAYS DURING THEIR LIFE CYCLE

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***Summary*—Different periods in the life cycle of protective relays merit different testing considerations. When a new type of distance relay is under consideration, acceptance (prequalification) tests are performed to validate manufacturers' specifications and relay functionality. When a substation design requires a certain functionality in the protection scheme, functional tests are performed to validate the relay against requirements before it is considered for the project. When a relay is installed in the field, commissioning tests are performed to validate the wiring and the interaction of the unit with the primary equipment and other intelligent electronic devices in the scheme. When the unit is in service, periodic tests may be performed to validate its functionality. In each period of the relay life cycle, judgment is required in the testing of the unit. Careful consideration and background information should guide the test procedure. This paper uses line distance relay elements as examples to illustrate specific concepts.**

***Keywords*—Relay life cycle–Relay testing–Distance relay.**

I. INTRODUCTION

Protective relays have a long history in the electric power industry. Their design principles, components, functionality, complexity, size, and other characteristics have evolved over decades. However, their main functionality—to protect power system elements (lines, transformers, and so on)—has not changed over time, and they remain a fundamental component of power systems. Modern protective relays are computers with flexible functionality that provide a wealth of information to the user [1]. Testing considerations need to adjust to account for the large amount of flexibility and information in modern intelligent electronic devices (IEDs) [2]. Fortunately, since the early days of numerical protective relays, there has been literature to provide guidance for testing them [3] [4]. This paper discusses relay testing concepts, using line distance relay elements as examples.

Manufacturers follow their own design and manufacturing practices to provide products that are competitive and that follow industry standards. The characteristics and specifications are public and published in data sheets or instruction manuals. The tests to validate conformance to standards are called type tests, and there is a test certificate or report associated with these tests. In some cases, a third-party certificate is obtained to validate conformance to an industry standard. Most manufacturers subject units to final manufacturing tests. A test report is often included with an IED.

When a particular model of a protective relay is considered for application by a utility for the first time, utility engineers typically require that the IED conform to certain standards and they verify its functionality. Utilities have acceptance criteria published for manufacturers that the model must satisfy [5]. The requirements may call for specific types of testing to qualify the model for application in the power system. Proof of compliance to standards may also be requested. The most important aspect of verification, however, is for engineers and technicians to familiarize themselves with and clearly understand the functionality of the unit.

Acceptance testing has different meanings to different users [3] [4]. Functional tests are often performed by electric utilities to validate the published functionality and specifications of a device and to get a full understanding of its capabilities. Some utilities additionally evaluate the relay in a real-time digital

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simulation environment by applying the relay to a model of their power system. Once the characteristics and functionality of the device are fully understood, the model is fully qualified.

Specific tests may be required by a utility, particularly with multifunction relays, to certify the functionality for particular applications in the power system. In a given project, the functionality required of a line protection relay can be different from that of the same model used in a previous project.

Acceptance testing can also mean testing a group of IEDs upon receipt to ensure that all (or a certain percentage) of them are operating properly, that the device model is the correct one, and that the units have not been damaged during shipment.

Commissioning testing should validate the functionality of the relay for a particular application. Commissioning testing is specific, and there are guidelines to follow [2] [6] [7]. With modern multifunction protective relays, testing the functionality for an application can be much more demanding than in the era of single-function protective relays. As such, the testing should only focus on the specific functionalities required from the IED.

Maintenance testing can be performed to ensure that an IED is performing correctly after it is in service. Protective relays are designed for decades of continuous operation. Modern numerical relays have drastically reduced periodic maintenance requirements versus previous technologies [8] [9]. The relays implement self-testing and can report hardware problems so that users can take action [10]. Self-testing is available for most IED hardware; most likely, the only hardware not self-tested is the binary outputs. Some users have devised means to monitor these automatically as well to complement the IED self-tests [11].

II. Evolution of Protective Relays

The electric power industry is over a century old, but power system components still experience failures that need to be detected and isolated promptly. Protective relays are key components in the protection and control of power systems, and they have evolved with advancements in power system technology [2] [12].

A. Electromechanical and Solid-State Relays

Electromechanical relays were based on ingenious applications of electromechanical forces to close contacts. These were generally single-function devices with moving parts that required calibration. For example, the implementation of a basic distance element required tapped transformers and inductors as well as variable resistors. These components produced torques and forces based on electromagnetic induction.

Following the invention of the transistor and solid-state components, for a brief period of time, protective relays shifted toward these technologies. Solid-state protective relays used transistor and operational amplifier technology [2] [12]. The same operating equations used by electromechanical relays were possible with solid-state technology.

For example, a classic implementation of a mho distance element considers two signals, S1 (operating) and S2 (polarizing), that should coincide for at least 180 degrees (±90 degrees or 0–180 degrees) [13]. S1 is calculated as shown in (1), and S2 is calculated as shown in (2).

$$S1 = V - Zset\, I \tag{1}$$

$$S2 = V \tag{2}$$

where:

V is measured voltage.

I is operating current.

Zset is relay reach.

The angle coincidence can be implemented with an electromechanical single-phase motor, as shown in Fig. 1a, or a solid-state circuit with squared signals and operational amplifiers or transistors, as shown in Fig. 1b [12] [13]. Both implementations provide the same characteristic result of a mho distance element.

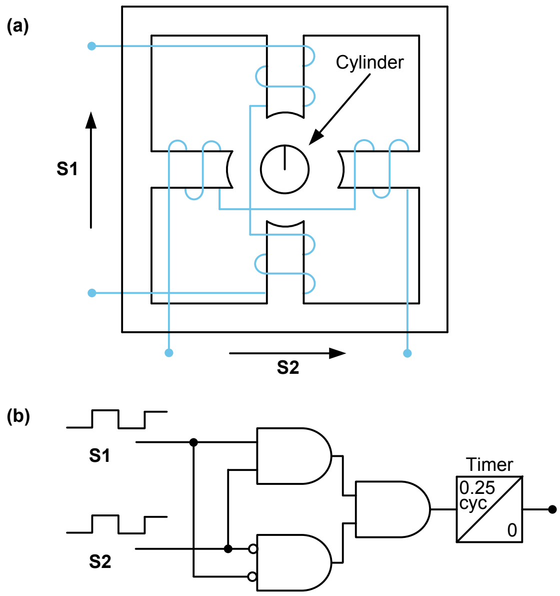

Fig. 1. a) Electromechanical and b) solid-state implementations of a classic mho distance element.

The cylinder in Fig. 1a has an axis of rotation. Springs and permanent magnets in the design produce torques that should be overcome by the torque produced by the angle coincidence of S1 and S2. In electromechanical relays, setting operating times and characteristics required careful testing and setting of spring torques, damping of magnet distances, and so on. These devices required periodic calibration of their characteristics because these could change over time.

In solid-state technology, like the element shown in Fig. 1b, timers were implemented with RC time constants. The resistive parameter had to be set carefully to provide the required timing for an assumed value of the capacitance. The RC time circuit had to provide a quarter-cycle coincidence for a 90-degree characteristic. There were other aspects of the design that required testing and calibration as well. The value of R or C could change over time, thereby changing the characteristic of the relay element. Maintenance testing was very critical for this technology.

These two technologies comprise the protective relay designs available prior to numerical IEDs. Both had requirements for periodic testing of their characteristics because they could lose calibration over time. The theoretical mho distance element implemented with (1) and (2) could drastically change its characteristics if resistor values or spring tensions lost calibration.

B. Numerical Protective Relays

Numerical protective relays are computers that run a program at specific time intervals. They have a microprocessor or microcontroller that has been programmed to continuously follow instructions.

A typical numerical relay architecture is shown in Fig. 2. The power system voltages and currents are sampled (Fig. 2a) and these numbers (hence the name "numerical relays") are sent to digital filters to extract the quantities of interest (Fig. 2b) using a cosine filter, for example. Most numerical relays extract the fundamental component (50 Hz or 60 Hz, depending on the power system), and a few extract the root-mean-square (rms) and harmonic quantities as well.

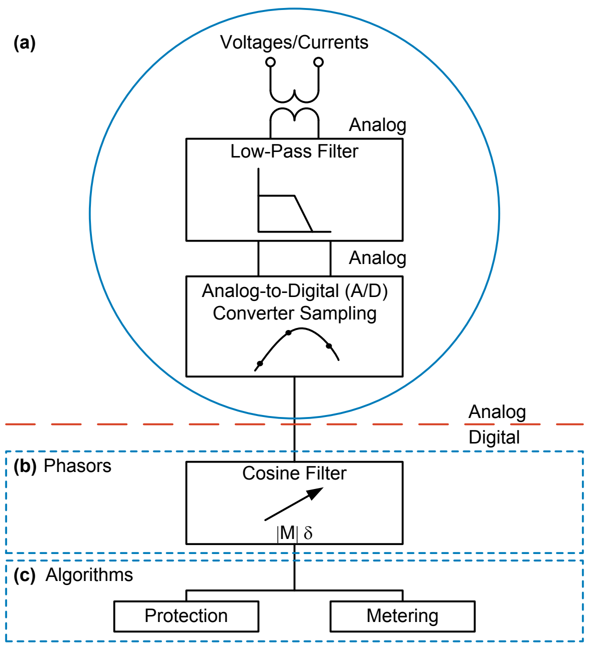

Fig. 2. Numerical protective relay.

If the process in Fig. 2a and Fig. 2b is working properly, the metering and protection algorithms of Fig. 2c will function correctly. The display of metered values is an indication that the protection algorithms are functioning properly.

As opposed to electromechanical and solid-state designs, in numerical relays, most of the processing happens in software instead of hardware. For example, the implementation of the same mho distance element described by (1) and (2) and the ±90 degree coincidence are performed using numbers and mathematical techniques. It is a program that runs endlessly; every processing interval, it calculates the numbers needed to implement the protective relaying elements [14].

There is little that can change in numerical relay hardware during the life cycle of the unit, and present designs ensure that the natural degradation of any component (the anti-aliasing filter, for example) does not affect the data acquisition process. Transformers and A/D circuitry have proven to be stable over time. Also, the program running in the relay does not change over the life cycle of the device.

Having a microprocessor also enables checks to ensure that the hardware is properly running [12]. These checks are called self-tests or watch dog monitoring. When these checks fail, the relay disables itself and issues an alarm to the user. The checks monitor power supply voltage levels and A/D subsystem offsets, which covers the failure issues of the relay shown in Fig. 2. However, the binary output contacts cannot be checked without certain wiring tricks [11].

III. Testing Stages Over the Numerical Relay Life Cycle

This section illustrates generic topics related to the testing of numerical relays by reviewing ideas discussed in the literature [2–10]. As mentioned in the previous section, a generic line distance relay element is used as an example. In the Appendix, the methodology used by one large utility is described to illustrate and contrast some of the ideas discussed in this section.

A. Acceptance Testing

Acceptance tests are also called prequalification or evaluation tests. They are used by electric utilities to qualify new relay models for application in the power system. The data sheet and instruction manual of the device can provide valuable information about the functionality of the device. Validation can also be requested via certain test certificates.

Utilities can borrow or purchase a unit from the manufacturer to perform detailed testing of crucial functions. Functional testing and verification of the IED's published characteristics provide valuable information to prospective users. The users learn how to interpret the behavior of the IED and learn a great deal about its design. In some cases, power system simulators are used to qualify protective relays [15]. While this kind of testing is expensive and involved, the user can gain a great deal of confidence in the equipment after simulated faults validate its functionality.

Acceptance testing can also refer to the tests needed when accepting a large order of IEDs. Factory inspection and sample testing of units (i.e., factory acceptance testing [FAT]) may be requested.

The common denominator in all of these acceptance testing activities is the exchange of information between the user and the manufacturer. It is in the interests of the manufacturer to provide all of the information requested by the user to obtain qualification for the device [5]. A data sheet and test certificates should be available from the manufacturer. The data sheet of the unit can clearly describe the characteristics of the functionality being considered. Taking a quadrilateral ground distance element as an example, Fig. 3 shows the pertinent information for the element for a protective relay.

The datasheet should clearly describe the functionality with setting parameters. For example, Fig. 3 shows the resistive and reactive reaches for the quadrilateral ground distance element.

Quadrilateral Ground Distance Elements

Zones 1-5 Impedance Reach

Quadrilateral Reactance Reach

5 A Model:	OFF, 0.05 to 64 Ω secondary, 0.01 Ω steps
1 A Model:	OFF, 0.25 to 320 Ω secondary, 0.01 Ω steps

Quadrilateral Resistance Reach

5 A Model:	OFF, 0.05 to 50 Ω secondary, 0.01 Ω steps
1 A Model:	OFF, 0.25 to 250 Ω secondary, 0.01 Ω steps

Sensitivity

5 A Model:	0.5 A secondary
1 A Model:	0.1 A secondary (Minimum sensitivity is controlled by the pickup of the supervising phase and residual overcurrent elements for each zone.)

Accuracy (Steady State):	±3% of setting at line angle for SIR <30 ±5% of setting at line angle for 30 ≤ SIR ≤ 60
Transient Overreach:	<5% of setting plus steady-state accuracy

Fig. 3. Example of a data sheet.

Certain hardware-oriented test certificates can also be requested from a manufacturer. Protective relays are designed to meet or exceed industry standards. For example, the IEC 60255 and IEEE C37.90 standards provide standard tests and requirements for electromagnetic compatibility and other aspects of the relay. It is also very common that homologation and/or familiarization with the functionality of a protective relay are achieved via testing in a utility's laboratories. In this environment, detailed investigation and testing can be performed with different approaches. Often, a source of voltages and currents (test set) simulates the voltages and currents coming from the power system. In this way, the protective relaying functionality is understood and verified.

For numerical relays, algorithms are tested and proven by the manufacturer with test protocols, as documented by type test certificates. Moreover, if the protective relay has been in production for many years, chances are that it has been part of many different applications. The goal of acceptance testing is to learn and validate the functionality of the protective relay and evaluate its design and performance for particular power system requirements. Detailed testing can be performed per the utility's standards, historic oscillography events can be replayed to verify the desired behavior, and programmable logic can be tested and verified.

It is becoming more common for users to have access to real-time power system simulators. Users can evaluate relay performance with evaluation cases simulated in real time on a model of their own power system. This testing is closed-loop testing in which the power system model is directly influenced by the behavior of the protective relay under test.

It is, however, far more common to use a test set for relay testing. As an example, the quadrilateral ground distance element characteristic described in [13] can be plotted manually or automatically with test equipment (see Fig. 4 and Fig. 5).

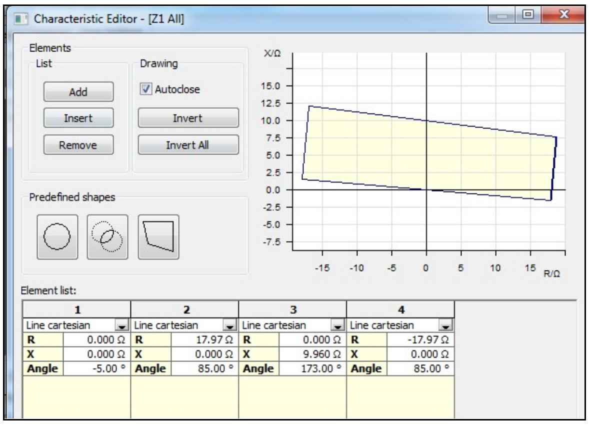

Fig. 4. Automated testing setup for a quadrilateral ground distance element.

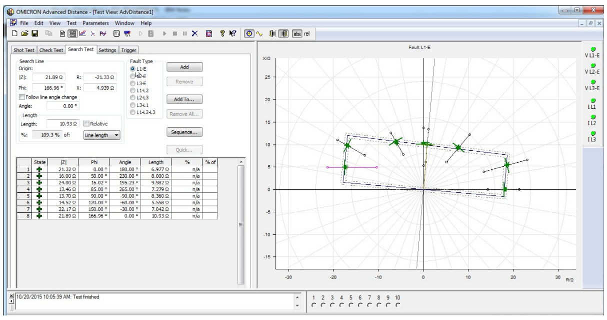

Fig. 5. Automated testing results for a quadrilateral ground distance element.

The test equipment has software to program and evaluate the tests to be performed. The user should understand the test software and the capabilities of the test equipment well so that the test results can be readily understood.

Fortunately, during this phase the testing is performed in a very controlled environment, generally with sufficient time to rectify issues. Careful understanding of the test software and the relay characteristics is required to obtain the proper results. During this period, if a test fails, it most likely due to parameters in the test software that were not properly set. For example, the following factors have been shown to influence the results of the quadrilateral ground distance element used as the example.

Distance elements are supervised by directional elements. Testing of the distance element characteristic should be done with a constant source impedance model to allow proper directional element decision making. In a constant source impedance model, the voltages and currents applied in the test are calculated for a simple power system with a single source and line impedance. Directional elements are designed under the assumption that for a forward fault, the V2/I2 (negative-sequence ratio) or V0/I0 (zero-sequence ratio) represent –Zs (the negative of the source impedance). If the directional element does not properly determine the direction to the fault, the distance element does not operate.

Quadrilateral elements have parameters that determine their plot on the R-X plane. Fig. 6 shows the characteristic of the example quadrilateral ground distance element.

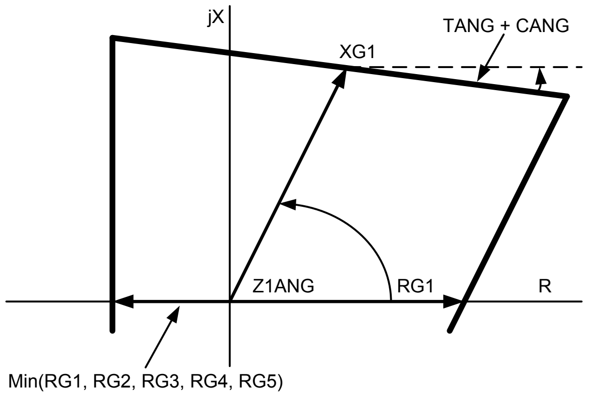

Fig. 6. Example of a quadrilateral ground distance element characteristic.

The TANG angle is a relay setting. The CANG angle is the angle difference between the line positive-sequence impedance and the angle of the zero-sequence impedance, as described in (3) [13].

$$\text{CANG} = -\arg\left(2 + \frac{\text{ZL0}}{\text{ZL1}}\right) \quad (3)$$

This angle is mostly ignored by users, but it can cause discrepancies between the observed and expected results. The automated testing software should consider shifts due to both angles.

The resistive lines for the quadrilateral elements should correspond to the relay characteristic. In the characteristic shown in Fig. 6, the right resistive element tilts with the line impedance angle. The left resistive line is vertical and corresponds to the minimum value of the setting for Zones 1–5.

Certain auxiliary functions that may interfere with testing should be disabled. For example, because of the way the automated testing operates, the loss-of-potential (LOP) function may block the operation of the elements and should be disabled.

In some designs there are dynamic characteristics based on certain measurements. For example, the I2/I1 magnitude ratio can be used to shift the right resistive line to the left for three-phase faults.

The main objectives of testing in this stage should be familiarization with and validation of the functionality that is required. Generally, acceptance testing covers the functions the user wants to verify and takes as long as necessary, within reasonable margins.

Visiting the factory and testing characteristics of certain functions prior to accepting a protective relay are also common activities. Users can also perform spot checks of certain IED functions and review the manufacturing process and quality programs. This activity allows users to learn about the quality programs used by the manufacturer in the manufacturing of the IEDs.

B. Commissioning Testing

The commissioning of the protection systems in an electrical installation (e.g., a substation or power plant) should be a planned activity with intelligent choices. The idea is to perform the necessary testing of the relay functionality to prove the healthiness of the hardware, the set points, and integrity with other equipment or devices [6] [7]. For the particular IED being tested, most of the configuration work should have been completed in the laboratory. For the quadrilateral ground distance element example, testing of the characteristic should have occurred during acceptance testing. The characteristics of the protective relay should be known in detail prior to commissioning testing.

Fig. 7 shows four points that are sufficient to verify the settings of a quadrilateral ground distance element during commissioning. The reactive reach (X setting) and the resistive reach (R setting) can be tested with two points for each, one point outside the characteristic zone and the other point inside the characteristic zone.

Commissioning testing is an activity that places a great deal of stress on the engineers and technicians performing the work. The testing should be minimal but adequate to properly evaluate the relay functionality. It is therefore very appropriate to limit the testing to the minimum needed to validate the functionality required. The spot testing in Fig. 7 illustrates this point.

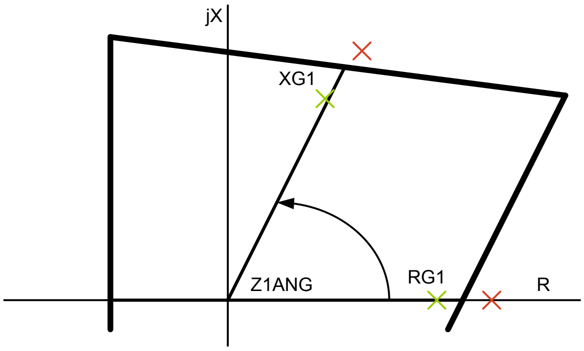

Fig. 7. Spot testing of the quadrilateral ground distance element (red points are outside the characteristic and green points are inside the characteristic).

The first test performed during commissioning should check the hardware healthiness and the proper wiring of binary and analog inputs. The relay metering functionality is also important. If the protective relay is metering properly, it is also executing the protective relaying functions properly.

Validating the protective relaying functionality during the acceptance testing period ensures that the already tested and known protective relaying functions are operating as tested in the laboratory.

Besides protective relaying functions, other checks are needed during commissioning. The wiring of the binary inputs and outputs should be checked carefully and validated. Functions or interlocks implemented in the programmable logic should be tested as well. Programmable logic in modern relays is very flexible, and the programmed functionality should be tested.

C. Maintenance Testing

Electromechanical and solid-state relays required injection boxes to test settings and also required manual setup (e.g., by adjusting screws and taps). By their nature, and depending on the amount of vibration present in the installation (power plants often have significant amounts of vibration), electromechanical and solid-state relays lose their calibration over time. Component degradation can also factor into this problem. Traditionally, therefore, utilities had a periodic (every two years or so) maintenance program to validate protective relay characteristics and settings [2] [3] [4].

One of the many benefits of numerical relays is that little to no maintenance is required [3]. Reference [8] discusses the maintenance interval for numerical IEDs with self-testing. The routine tests for numerical relays only include meter checks and binary output checks. If the relay is measuring properly, and no self-test has failed, there is no reason to test the relay further. Relay self-testing saves routine testing time [8].

The A/D conversion in modern numerical relays does not drift over time, and this subsystem is monitored by the self-test mechanism of the relay.

Fig. 8 shows a report from a line distance relay with a failure. The A/D conversion system has failed because the measured offset (which should be close to 0 mV) is outside set boundaries. The protective relay has disabled itself because the measurements it is receiving are not accurate; the A/D subsystem has clearly failed.

```
=>STA A

Failures
 A/D OFFSET FAILURE

Channel Offsets (mV) W=Warn F=Fail
 CH1 CH2 CH3 CH4 CH5 CH6 CH7 CH8 CH9 CH10 CH11 CH12 MOF
  55F 56F 56F 59F 51F 54F 55F 56F 49F 49F  51F  52F -10

Power Supply Voltages (V) W=Warn F=Fail
 3.3V_PS  5V_PS  N5V_PS  15V_PS  N15V_PS
    3.29   4.98   -4.98   14.97   -14.99

Temperature
 41.1 Degrees Celsius

Communication Interfaces

Active High-Accuracy Time Synchronization Source: NONE
 IRIG-B Source Absent

Relay Programming Environment Errors
 No Errors

Relay Disabled
```

Fig. 8. A self-test report from a protective relay with a failure.

The situation in Fig. 8 shows the advantage of having intelligence in the relay to determine when there is a failure in the unit. This allows utilities to reconsider maintenance programs for protective relays in the following ways:

- After commissioning, continue to monitor the self-test functionality of protective relays.
- Over long periods, monitor the metering of protective relays. If the metering is correct, then the protective relay is sound. Metering values can be verified against those of other devices in the system.
- Devise an automatic comparison of metered values. This can be done with automation controllers automatically comparing the metering values of two devices measuring from the same location. If the measurements are the same, within a margin, then the protective relays are sound [16].

There are other approaches that take advantage of the reporting capabilities of numerical relays. For example, using time-synchronized measurements (synchrophasors), users can devise continuous testing schemes for the measurements. If a numerical relay is measuring properly, the protective relaying functionality is working properly.

Periodic testing of the relay output contacts to ensure that they are operational can also be implemented automatically. Protective relays may not take action for very long periods of time; making sure that they are available when needed is always a concern. Some clever schemes take advantage of programmable logic to test binary outputs, as described in [11].

IV. CONCLUSION

Modern protective relays have made the operation of power systems more reliable and efficient. Multifunction IEDs have several capabilities, and most of the protective relaying functionality is programmed in instructions that run continously in hardware. Having many capabilities in one device requires users to learn and verify what is published in the data sheet and instruction manual. This should be done in the laboratory, not the substation. Acceptance testing verifies that units meet the requirements for particular functions and protective relaying principles.

Modern protective relays are computers. Testing a single unit and making sure the protective relaying characteristiccs are correct implies that the tests are valid for all units with similar characteristics. The computer program running internally is the same and does not change over time.

One of the most stressful activities in a project is the commissioning stage. Commissioning testing can be made simpler and more efficient by focusing on testing key points in the characteristics of the relay. Commissioning testing should spot check certain points of the key functions. Most of the detailed functionality should have been tested in the laboratory during acceptance testing.

Maintenance testing should take advantage of the self-test functionality of protective relays. The only routine testing required for numerical relays is meter checks and binary output checks. The sequence of events (SOE) report and oscillography can be used to properly evaluate the operation of protective relays and determine if any maintenance testing is needed.

V. APPENDIX

An electric utility in the United Arab Emirates the authors have worked with defines the testing throughout the life of their protective relays as follows.

A. Prequalification Tests

The manufacturer receives all of the necessary application details and proposes a relay model with specific options (hardware and software) to meet the application needs.

The relay manufacturer visits the utility and provides a presentation about the relay features. The presentation includes an exchange of ideas and discussion about how to apply the device to the application.

The manufacturer's technical representative and a utility engineer jointly develop a wiring template and the relay configuration file for the application. The manufacturer sends a sample relay for the utility engineers to test and become familiar with.

Upon agreement between the manufacturer and the utility, the sample relay is tested (with the agreed upon configuration file) in a real-time power system simulator to validate the performance requirements for the particular application. The main objectives are to validate the main protective functions for selectivity and operating time for internal faults, to validate security for external faults, and to fine-tune the setting parameters.

B. Laboratory Acceptance Tests

The utility engineers and manufacturer's technical representative use the finalized configuration file approved after the real-time simulator testing to review in detail the characteristics of the unit. The utility verifies the relay element pickup characteristics and validates the operating times. At this time, the full characteristics of the distance elements, for example, are plotted and verified.

C. Commissioning Tests

Commissioning tests focus on the integration of the device into the overall scheme for protection and control in the substation. A few test points are selected to validate functionality. No detailed plots of characteristics are programmed in the test protocol. The wiring and programmed logic functions are verified together with any communications of parameters to the control center.

D. Maintenance Tests

No routine maintenance tests are programmed for numerical relays. The utility fully relies on the internal self-tests of the devices.

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VII. BIOGRAPHIES

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Rajkumar Swaminathan is a protection engineering manager in the sales and customer service division of Schweitzer Engineering Laboratories, Inc. (SEL). He received his bachelor's degree in electrical and electronics engineering from the University of Madras, India, in 1997. Rajkumar has over 15 years of experience in power system protection application, design, testing, and commissioning. He worked as a commissioning engineer at M/S Voltech Engineers in India and as a senior technical support engineer at Schneider Electric in Saudi Arabia before joining SEL Bahrain.

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