Automated Protection Engineering Process from Standards and Simulation Studies to IED Configuration

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***Abstract*— Modern power system protection and control relays or Intelligent Electronic Devices (IEDs) are developed with integrated functions including protection and control elements, measurements, self-tests and monitoring, and advanced communications capabilities, that enable client-server and peer-to-peer message exchanges through a high-speed network. In comparison with previous single-function electro-mechanical protection relays, these multi-function numerical relays or IEDs have many obvious advantages and benefits. However, the effort spent on understanding how the integrated functions work together and the complexity of configuring the devices to work correctly and reliably have become a big challenge for utility protection and automation engineering groups, especially with increasing workload and aging work forces. Statistics show that incorrect setting, logic, and design errors associated with numerical relays are among the top causes of misoperations for utility power networks.**

There is an increased interest for the industry to reduce the complexity introduced by protection IEDs due to multi-functionality by simplifying the IED configuration through functional optimization and artificial intelligence. Meanwhile, there is also a great amount of need to establish the data link between different aspects of protection engineering processes to improve efficiency and accuracy.

In this paper, the existing protection engineering process is first evaluated to identify the gaps and repetitive work in a typical protection engineering group. The proposed solution is then presented and implemented into an automated tool for the protection engineering process with consideration of (i) reducing or eliminating manual data transfer, (ii) customized engineering documentation production, (iii) training of new protection engineers, (iv) enforcement of standards and compliance, (v) accumulated protection engineering experience, (vi) feedback from other stakeholders such as the automation engineering group and field-testing engineers. Utility protection engineers will benefit from the proposed solution of increased productivity and accuracy without losing the understanding of protection philosophy.

***Index Terms*— Intelligent Electronic Devices (IEDs), Automated Protective Relay Settings Tool, CIP Compliance Studies, Protective Relay Setting and Calculation.**

I. INTRODUCTION

THE microprocessor-based multi-functional protection relays have been widely used in power systems to provide many benefits including cost reduction and improved system performance, monitoring, digitalization, communication technology, and compliance. However, the complexity of setting up or configuring the devices to work as designed or expected becomes more challenging due to the information and knowledge required to configure and deploy the device. Below are a few tasks that are typically required to configure a protective relay.

a. Collection of system data, studies, and simulation has to be completed first in order to derive the protection setpoints required by the protection relays. This also includes following the utility or national standards, guides, common practices, and compliance standards.
b. Engineered protection logics must be designed and programmed to work seamlessly with the device's internal logics implemented in firmware such as breaker failure, auto-reclose, single-pole tripping, and tele-protection schemes.
c. Input and output configuration per DC schematic drawings, as well as communication message mappings according to the data mapping point lists.
d. Additional setpoints for monitoring device health, data integrity, cybersecurity, event recording and archiving, synchronized clock, and so on.

To reduce the complexity and save engineering effort on programming and testing, there is an increased interest in reducing the complexity introduced by protection IEDs by simplifying the IED configuration through functional optimization and artificial intelligence. At the same time, many utilities have created setting templates to standardize the protection and control logic communication mapping, and some other common setpoints. However, the effort to come up with correct protective settings, configuring the devices, creating testing procedures, and providing evidence of compliance cannot be standardized due to the nature of work. Currently there is still a lot of manual work for passing the data, checking standards, performing calculations, entering the setpoints, and creating test procedures. According to WECC's 2019 misoperation report [1], around 48% of all misoperations can be attributed to one of the cause categories related to human performance ("incorrect setting/logic/design errors" is listed at 42% and "as-left personal error" is listed at 6%). Automatically tracking and handling the information that is required for setting calculation and verification can be achieved through the Automated Protection Engineering Process (APEP). This automated process bridges the gaps among the short circuit study, setting calculation, coordination study, and configuration of protective relays. This not only reduces copy/paste errors, but also provides the following benefits:

i) Reducing or eliminating manual data transfer
ii) Improved production of customized engineering documentation

iii) Training of new protection engineers
iv) Enforcement of standards and compliance
v) Accumulated protection engineering experience and feedback from other stakeholders such as automation engineering groups and field-testing engineers
vi) Increased productivity and accuracy without losing the understanding of protection philosophy.

II. EXISTING UTILITY PRACTICES

Compared with older single-function electromechanical (EM) or solid-state relays, IEDs provide enhanced capabilities in protecting increasingly complex power systems. The business drivers to upgrade IEDs from EM relays have been discussed in detail in reference [2]. Digital protection relay or IED settings include system-specific settings such as details of the protected and monitored equipment (e.g., buses, transformers, transmission lines, loads, instrument transformers, switchgear, etc.) or IED-specific settings (e.g., IED wiring, connection, protection functions, protection pick-up values, I/O configuration, communication schemes, etc.)

As stated before, modern protection relays or IEDs could have thousands of setpoints which include basic product setup, communication, logic and protection schemes, group of protection functions, and inputs/outputs. The protection functions and communication, particularly for IEC 61850 digital substation applications, are so closely related to each other that it requires the protection engineers to not only have a good understanding of power system protection, but also communication technology expertise to realize the required protection schemes. Due to the increased complexity of setting up a digital protection relay and the lack of experienced workforce, automating the protection engineering process through intelligent software tools is gaining attraction due to efficiency and accuracy. This section first analyzes the complexities of digital relay settings and optimizing the determination of some critical protection setpoints, followed by the existing utility practices and challenges that the paper is trying to resolve.

A. Complexity of Multi-function Digital Relays

For a protection relay to work properly, it requires functioning hardware, validated firmware, and correct configuration of setpoints.

The hardware architecture of a typical protection relay is shown in Fig. 1. Typical subsystems include a signal conditioning front-end, analog-to-digital conversion (ADC), central processing unit (CPU), communication module (serial, copper, or fiber), inputs and outputs, internal memory, and a power supply module. Other parts include a clock signal card, LCD display, keypads, and pushbuttons.

The firmware or software is the algorithm or application that is developed by relay manufacturers to operate on a real-time operating system (RTOS) such as VxWorks. It may include the functions for system services, HMI, applications such as protection, communication, metering, data archiving, and real-time clock, and auxiliary functions such as healthy monitoring and self-testing, security, and safety.

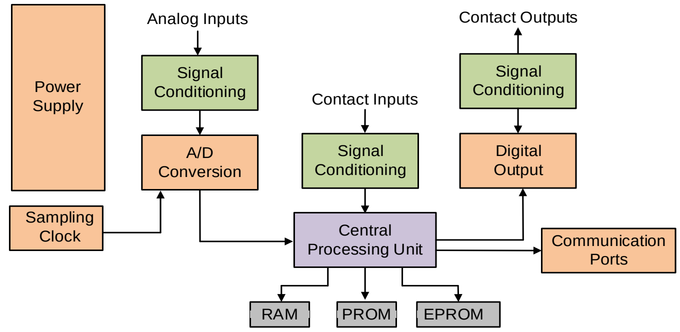


Fig. 1. Architecture of a microprocessor protection relay

The setpoints are typically configured through a relay configuration software tool and are often in the format of a setting file that is provided by actual relay manufacturers. These setpoints are required for the relays to work per the requirements defined by protection and automation engineers. Relay manufacturers often categorize the setpoints into different groups based on their functionalities such as product setup, system setup, protection group settings, protection logic and schemes, and input/output configuration. An example of a digital relay and its functions [3] is shown in Fig. 2 below. As can be observed, this protection relay has many protection functions that are required for protecting two feeders.

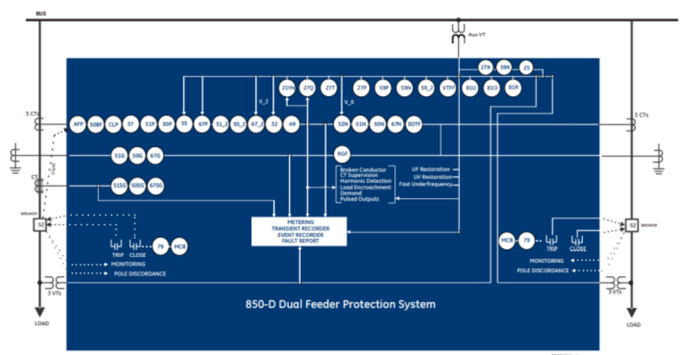


Fig. 2. Digital relay and its functions

B. Optimizing Protective Relay Setpoints

A relay setpoint is a setting or configuration that is designed to make the relay work as expected. For example, the pick-up setpoint of an instantaneous over-current relay means the relay would operate when the current reaches or exceeds the pick-up value such that the circuit breaker can be opened to clear the fault. Traditionally, the setpoints of a protection relay are entered as secondary values since a Current Transformer (CT) or a Voltage Transformer (VT) has to be used for connecting to protection relays. Some relay configuration tools allow the engineer to use either primary or secondary values.

As shown in Fig. 2, a modern digital relay has many protection functions integrated into one box and could have hundreds or thousands of settings in order for the relay to work as expected. Configuration of a protection relay will require the following information to start:

a. AC/DC schematic drawings for conventional hardwired I/O substations, and a virtual I/O mapping points document for digital substations
b. The short circuit study and coordination study for determining the protective setpoints
c. Utility and industry standards to be followed while creating the setpoints
d. Requirements for communication, real-time clock, archiving, and cybersecurity.

This can be tedious and time-consuming and human error can occur. Consequently, the relay will mis-operate if not caught during the peer-review and commissioning testing stages.

A very important task for a protection relay manufacturer is to simplify the configuration of a protection relay. For example, the distance protection for a transmission line measures the impedance between the relay location and the fault location, and compares it with the setpoint. If the impedance measured is lower than the setpoint, the relay will operate and isolate the fault. There are several variations on how to create the setpoint for a digital relay. Table 1 lists the system parameters that are required for the relay system setup for the protected line. Table 2 lists the setpoints used by relays from different manufacturers. Both Relay-A and Relay-B require the user to calculate a secondary Ohm, even though the line parameter is given in the line configuration. The default setpoints for distance Z1 reach and Z1 RCA makes no reference to line parameters. While Relay-C only requires entering a line percentage for the reach, with a default value that agrees with the distance relay protection principle. Relay-C hides some settings for advanced users who would like to finetune the settings with secondary Ohms and RCA angle. There is no doubt that Relay-C provides better setting simplification than Relay-A and Relay-B. It can be further improved as shown in Table 3, where the yellow background is entered by the user and the green background is for information only and changes as the user enters the value. There are a lot of other features that can be added to simplify the configuration and some self-check functions can also be implemented to improve the configuration tool.

Table 1: System data for a distance relay

Rated Voltage	230kV
CT Ratio	2000/5A
PT Ratio	3000/1
Line Positive Impedance (secondary)	4.54 Ohms , 85 deg
Line Zero Sequence Impedance (secondary)	15.32 Ohms, 72 deg
Line length	56.9 miles

Table 2: Distance function setpoints (Z1 as an example)

A Relay		B Relay		C Relay	
Function	Enable/Disable	Mho Enable (E21MP)	N, 1-5	Setting Mode	Simple/Advanced
Z1 Direction	Forward/Reverse	Quad Enable (E21XG)	N, 1-5	Function	Enable/Disabled
Shape	Mho/Quad			Shape	Mho/Quad
Reach	3.62 ohms	Z1 Reach (Z1MP)	3.62 ohms	Z1 Reach (simple)	80%
RCA	85 deg			Z1 Reach (Advanced)	3.62 Ohms
				RCA (Advanced)	85 deg

Table 3: Distance function setpoints (increased usability)

Rated Voltage	230kV		
CT Ratio	2000/5A		
PT Ratio	3000/1		
Line Positive Impedance (Primary)	34.05 Ohms , 85 deg	Secondary	4.54 Ohms , 85 deg
Line Zero Sequence Impedance (Primary)	114.9 Ohms, 72 deg	Secondary	15.32 Ohms, 72 deg
Line length	56.9 miles		
C Relay			
Function	Enable/Disabled		
Shape	Mho/Quad		
Z1 Reach	80%	Secondary	3.62 Ohms
RCA	85 deg		

C. Existing Utility Practices and Challenges

Utilities have used many methods to simplify the configuration of protective relays in order to comply with relevant standards and reduce common errors while creating the setting file for digital relays. The simplifications include:

a. Use of logic and protection scheme templates that have been tested in the lab and field. A logic diagram drawing or relay template setting file has been created for each type of relay such that all protection engineers can use them as a starting point when creating a new setting file for similar relay implementation.
b. Use of setting calculation templates created in Mathcad or Microsoft Excel to make sure protection engineers follow the common practices required by utility and industry standards. Fig. 3 shows an example of a Zone-1 distance (Z1) setpoint calculation using Mathcad. Fig. 4 is an example using Microsoft Excel to realize the automated calculation of setpoints.
c. Automation of NERC compliance studies and test procedures using the setting calculation tool. Fig. 5 shows an example of PRC-023 loadability check.
d. Define unified communication point mapping for each type of relay to reduce the work for typical settings required for SCADA and relay-to-relay communication.

The power industry has also put a lot of effort into addressing these challenges, including:

a. The use of automated tools to manage relay databases and perform some analysis and reporting [4].
b. The use of synchro-phasor data or IEC 61850 sample value (SV) data for dynamic state estimation for power system protection and control [5].

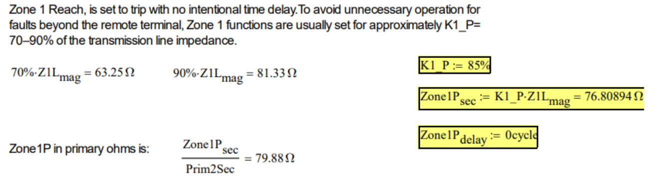
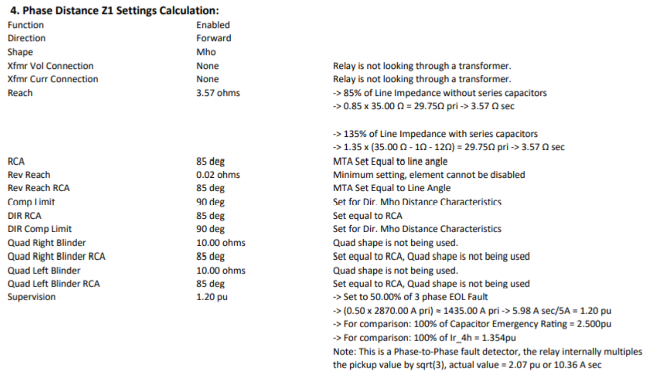


Fig. 3. Relay setpoint calculation using Mathcad



4. Phase Distance Z1 Settings Calculation:

Function	Enabled	
Direction	Forward	
Shape	Mho	
Xfmr Vol Connection	None	Relay is not looking through a transformer.
Xfmr Curr Connection	None	Relay is not looking through a transformer.
Reach	3.57 ohms	-> 85% of Line Impedance without series capacitors -> 0.85 x 35.00 Ω = 29.75Ω pri -> 3.57 Ω sec -> 135% of Line Impedance with series capacitors -> 1.35 x (35.00 Ω - 1Ω - 12Ω) = 29.75Ω pri -> 3.57 Ω sec
RCA	85 deg	MTA Set Equal to line angle
Rev Reach	0.02 ohms	Minimum setting, element cannot be disabled
Rev Reach RCA	85 deg	MTA Set Equal to Line Angle
Comp Limit	90 deg	Set for Dir. Mho Distance Characteristics
DIR RCA	85 deg	Set equal to RCA
DIR Comp Limit	90 deg	Set for Dir. Mho Distance Characteristics
Quad Right Blinder	10.00 ohms	Quad shape is not being used.
Quad Right Blinder RCA	85 deg	Set equal to RCA, Quad shape is not being used
Quad Left Blinder	10.00 ohms	Quad shape is not being used.
Quad Left Blinder RCA	85 deg	Set equal to RCA, Quad shape is not being used
Supervision	1.20 pu	-> Set to 50.00% of 3 phase EOL Fault -> (0.50 x 2870.00 A pri) ≈ 1435.00 A pri -> 5.98 A sec/5A = 1.20 pu -> For comparison: 100% of Capacitor Emergency Rating = 2.500pu -> For comparison: 100% of Ir_4h = 1.354pu Note: This is a Phase-to-Phase fault detector, the relay internally multiples the pickup value by sqrt(3), actual value = 2.07 pu or 10.36 A sec

Fig. 4. Relay setpoint calculation using Microsoft Excel

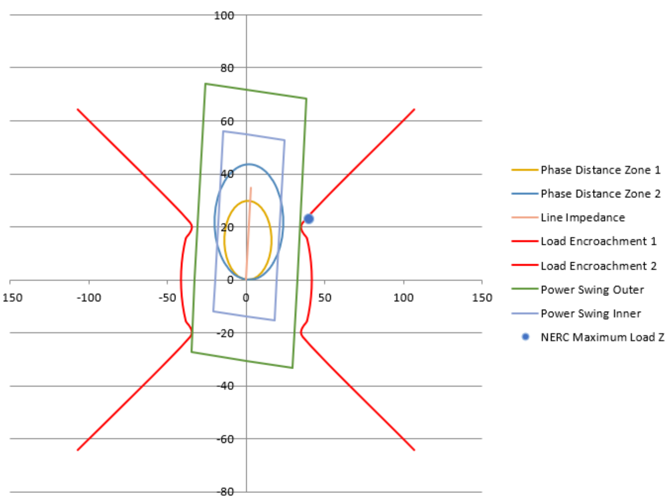


Fig. 5. NERC PRC-023 complicance check using setting calculation tool

III. AUTOMATED ENGINEERING PROCESS FOR PROTECTION SETTING FILE CREATION

As shown in Fig. 6, the proposed solution integrates the power system short circuit study, protection coordination study, utility and industry standards, setting calculation, compliance studies, test report, and creation of protection relay setting files into one engineering tool for protection engineers. The engineering tool interfaces with power system study software (e.g., ASPEN or CAPE) to perform the short circuit study and imports the study results automatically. Utility requirements, the protection setting guide, and NERC compliance standards can be customized and incorporated and enforce the standard practice within the utility. In addition to the interfaces, the engineering tool has four modules: setting calculation, compliance study, relay testing, and setting file creation. The modules can be customized to generate study reports, relay setting files, and test procedures.

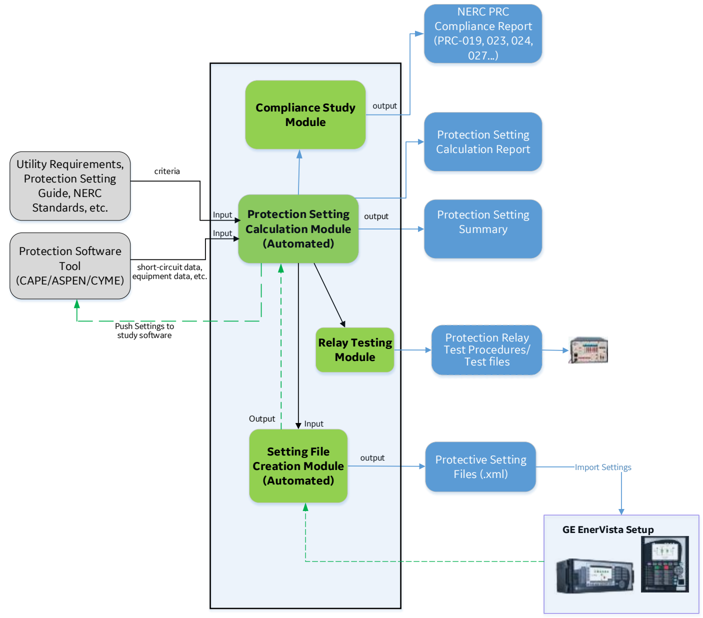


Fig. 6. Functional diagram of the automated engineering process for power system protection

A. *Setting Calculation*

This section interfaces the study software that is commonly used by utilities to perform required short circuit studies under specified contingencies. For example, the following criteria may need to be considered when calculating the distance zones' reach:

a. Source Impedance Ratio (SIR):

The source impedance can be derived from a 3LG fault on remote station bus. The equivalent impedance (Z_{1s}) in primary ohms is:

$$Z_{1s} = \frac{V_r - V_f}{I_f} \text{ --- } (1)$$

where:

V_r is the rated source voltage (Ph-G)

V_f is the voltage seen by the relay for a remote bus fault (Ph-G).

I_f is the fault current seen by the relay for a remote bus fault

The SIR can then be calculated by dividing the source impedance by the line impedance. The SIR defines the line length from the protection perspective: short line SIR>4; medium line SIR = 0.5~4; and long line SIR< 0.5. A high SIR is due to either a short line or weak source, and needs attention when setting the instantaneous distance or overcurrent elements, which may be disabled in some short line applications.

b. Loadability:

The distance relay must be set such that the relay is secured under maximum load. If this condition cannot be satisfied, then reach has to be reduced or the load encroachment function to be enabled such that the relay will not trip the circuit under maximum load condition. NERC PRC-023 has defined the maximum loadability and it can be calculated using the winter emergency rating of the line.

c. Apparent impedance under line outages:
One of the shortcomings of distance relays is that it can under-reach or over-reach under some system operation scenarios. This can be avoided by finding the apparent impedance seen by the relay by simulating faults under different operating contingencies (one-line outage, two-line outage, etc.).

B. Compliance Study

Utilities are mandated to adhere to approved internal standards or reliability standards developed by their regional regulatory entity. The proposed tool should be capable of automatically checking compliance to published standards.

This includes the following:

a. How to identify the generation and generation interconnection protection relays that are subject to the various NERC standards
b. How to set and verify the distance/loss-of-field/out-of-step protection elements for stable power swing compliance
c. How to set and verify the under- and over-frequency/voltage protection elements for generator protection and satisfying the NERC frequency and voltage ride through requirements
d. How to set and verify the over-excitation and loss-of-field protection elements to coordinate with generator excitation limiters. A customized compliance report will be available for utilities to provide evidence of compliance.

C. Relay Testing

The proposed tool integrates a Relay Testing Module (RTM) capable of automatically creating a test procedure based on the protection functions activated and using the settings already determined by the setting tool. The test procedure will have the test points and the values of the test quantities to be applied during commissioning. The test procedure generated can also be converted into a file format that can be uploaded onto a relay test set, reducing the time and effort required in creating test plans for relay tests set during commissioning.

If protection relays with a digital interface are to be tested, the setting tool can be directly used in the automated testing of such protection relays. Since the setting tool will be communicating directly with the protection relay, a “Test Passed” or “Test Failed” report can be automatically generated during tests.

D. Relay Setting File Creation

One of the main tasks of the automated engineering tool is to create the setting files that are comparable to IED configuration tools such that the tedious manual setpoint inputs can be avoided. This module can be customized to suit the IEDs from different vendors based on the utility needs. The tool will require an IED setting template file generated from the IED configuration file or created before through the utility standardization department. It will then import this manually and automatically update the protective setpoints without changing other setpoints in the template. This tool also allows users to create their own IED template, which can later be used for configuring a similar IED.

IV. Conclusions

This paper presents the efforts to bring protection engineering to a new level of automation, improving workflow, accuracy, and efficiency. The engineering tool also eliminates manual copy/paste errors through a bidirectional interaction with the study software and relay configuration software and generates a customized study and testing report. This tool can be further developed to interface with the Centralized Protection and Control (CPC) platform using virtual relays such that the CPC relays can be configured and validated through the interfaces of the engineering tool to the power system simulation software. Automated testing of protection relays can also be realized if the relays can provide a digital interface for testing.

In the future, automated engineering tools should support a multi-vendor environment. Also, such engineering tools should support the top-down or bottom-up engineering process of IEDs using communication protocols such as the IEC 61850, similar to IEC 61850 IED configuration tools. In addition, the management of protection devices, functions, and substation assets can be integrated into the automated engineering tool to support relay settings lifecycle management, asset maintenance plans, visualization of protection functions, fault and disturbance analysis, compliance reporting, centralization of relay information, automatic retrieval of information, and the creation of built-in templates for relay testing and site commissioning tests.

Utility protection engineers will benefit from the proposed solution with increased productivity and accuracy without losing the understanding of the protection philosophy.

V. References

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