Practical Implementation of the Stepped-Event Analysis in Protection Evaluation

Xinyang Dong, Ishwarjot Anand, Saman Alaeddini, Mehrdad Chapariha, *Quanta Technology, LLC.*
Scott Hayes, Aaron Feathers, *Pacific Gas & Electric*
Chris Bolton, Elliott Brown, *San Diego Gas & Electric® Company*

***Abstract*—Stepped-event Analysis (SEA) is an event-based simulation method that provides visibility to the evolving impact of faults in protection systems, where the fault current and voltages are changing due to the sequential opening of a breaker or a fuse. For years, this method has been promoted as an effective methodology to validate the settings and coordination between primary and backup protection systems.**

With the advent of new software applications capable of such analysis, the SEA method has become more mainstream. It has been increasingly adopted as the tool to ensure compliance with NERC PRC-027 Requirement R2. The same method can be leveraged to evaluate worst-case fault clearing time for Single Point of Failure conditions to support NERC TPL 001 requirements. However, determining the simulation and model preparation requirements, which are based on various network conditions and different short circuit software platforms, remains a challenge in the industry. Another challenge is that SEA-based simulations are computational-heavy in nature, which requires careful selection in setting up fault location, contingencies, and other study inputs. Other common challenges are special network topologies or simulation environments with both transmission and distribution protection models. These simulation scenarios can vary for different utilities due to the unique nature of their systems. This paper will provide protection engineers a reference in determining the implementation strategy and dealing with the common challenges.

***Keywords*— Stepped-event Analysis, Power System Protection, Relay Coordination, NERC Compliance**

I. INTRODUCTION

The growing emphasis on efficiently meeting the requirements of NERC compliance standards, and special programs, such as PSPS (Public Safety Power Shutoffs), has significantly increased the need for detailed power systems protection evaluation.

The NERC PRC-027-1 standard, which has been in effect since April 1, 2021, requires utilities that own protection systems for Bulk Electric System (BES) elements to establish processes to perform system-wide protection coordination review on a regular basis, thus posing a great challenge for them [1]. The NERC TPL-001-4 standard and the upcoming revision TPL-001-5.1 (effective July 1, 2023) aim to establish transmission planning performance requirements to ensure that the bulk electric system (BES) will operate reliably over a broad spectrum of system conditions and following a wide range of probable outages. It requires transmission planners to perform numerous planning studies based on the standard's contingencies and event requirements, some of which are highly dependent upon the protection system design and operation for determining the accurate definition of contingencies, for example, events that have a delayed fault clearing time due to the failure of a non-redundant relay protecting the faulted equipment [2]. Additionally, the PSPS program, which is a seasonal program adopted by California's electricity utilities, actively cuts power to lines and equipment to prevent wildfire, imposes very short turnaround times for protection system performance and reliability review with the new network conditions.

The challenges described above demand a systematic and efficient method for thoroughly evaluating the protection system performance under a variety of system conditions. Stepped-event Analysis (SEA) is a well-known technique for evaluating the protection system performance that can be effectively utilized to meet the requirements of the types of protection studies discussed above [3]. The following chapters describe the SEA methodology and discuss practical implementation challenges related to both technical and data management.

II. STEPPED-EVENT ANALYSIS (SEA) OVERVIEW

SEA is a protection evaluation technique, which involves simulation of faults under various network conditions, and prediction of sequential operation of protection elements. It starts with a fault application and either ends with enough operations of breakers to isolate the fault from the rest of the system, or ends with fault not being cleared even after all protection systems have dropped out.

A more traditional way of fault analysis is to calculate relays operation based on the simulated fault voltage and current after the application of a fault. This method is very useful and sufficient in a lot of studies, but it is limited to only consider the fault parameters immediately after fault happens. In real world, a series of breakers open after the fault and every breaker open causes a change in the network and the fault voltage and current. This change can be picked up by relays, resulting in changes in initially expected operations of relays—the relay may no longer see the fault or start to see the fault. Traditionally, protection engineers would manually identify the worst-case breaker operation sequence or network conditions to evaluate the protection system performance; however, this can be quite overwhelming, especially for a congested network with many protection devices.

SEA-based simulations consider the network changes that occur due to sequential protection operation and break down the fault simulation into different events. Each event is defined by the opening of one breaker or multiple if they operate at the same time. At each event, the voltages and currents seen by the protective devices located around the faulted element are recalculated and their steady-state operation is predicted.

The industry-standard short circuit software platforms provide standard macros/scripts to perform SEA-based simulations with the ability to customize simulation parameters [4], [5]. However, some of the challenges and solutions described in the paper require development of custom macros/scripts that leverage the simulation and scripting capabilities of these software platforms.

III. STEPPED-EVENT ANALYSIS (SEA) IMPLEMENTATION

While the fundamentals of SEA can be applied broadly to study various types of equipment and protection schemes, there are certain factors that need to be considered during the design and practical implementation of SEA-based simulations. The following subsections briefly discuss the various factors impacting the simulation design.

A. Modeling Requirements

Besides an accurate and detailed short circuit network model, SEA requires a highly consistent and simulation-ready protection model. There are two aspects of simulation-readiness that need to be considered:

1) Device-level readiness: This typically involves adding protective relay device models, adding CT and VT ratios and connectivity, and adding tripping logic i.e., defining which protection elements can result in breaker operation and whether they are supervised by other protection elements.

2) Network-level readiness: This involves ensuring that protection is modeled on an adequate area within the network. Typically, when performing the simulations on a network element, protection shall be modeled on the network element under study, as well as on all adjacent network elements that require coordination.

The minimum requirement for SEA is to model basic protective functions that are sufficient to clear the fault in a reasonable time. This could represent the protection system when communication channels are out of service, and the system relies on bare minimum protection, simulating the worst-case protection contingency condition.

Figure III-1 shows the hierarchy of protection modeling details. The peak represents the most detailed protection models that include all protective devices, communication schemes, and different operation times of breakers. The bottom of the triangle represents the most basic protection model, including only the important distance and overcurrent elements. Each level requires the level below it to support the modeling: for example, the fault detection model can only be created when the basic models of distance and overcurrent exist.

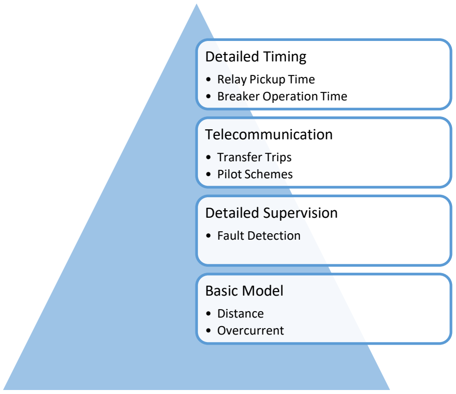

Figure III-1 Protection Modeling Hierarchy

Depending on protection philosophy and modeling details, minimal modeling of protective relays may not be enough, and it may result in many false mis-operation flags during simulation studies. In this case, more detailed modeling is required. Protection model can be improved by modeling differential protections, teleprotection schemes, and transfer trip schemes. Any added detail requires support from the simulation tool as well as the availability of data.

Data integrity, and robust model maintenance processes are key to the successful preparation of models required for performing SEA. These aspects are discussed in more detail in Chapter 4.

B. Simulation Design Parameters

1) Simulation Area

Simulation Area is the area of the network in which the operations of protective relays are evaluated during the fault simulation. It is defined by simulation depth/tier number, which is an integer that counts how many real buses away the furthest elements are from the element under study.

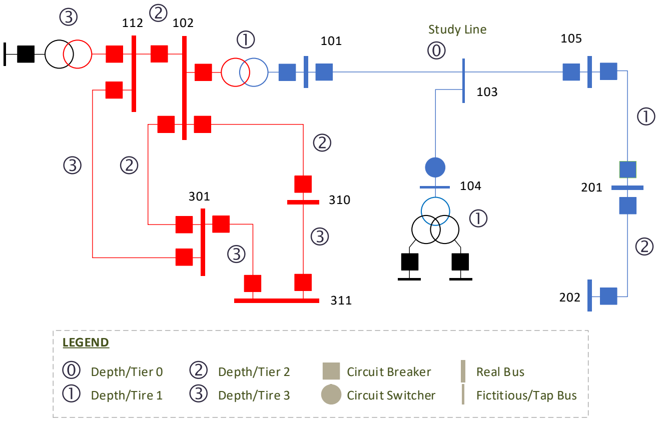

Figure III-2 Simulation Area Around Study Line

Figure III-2 shows the network elements that are covered over different simulation depths ranging from 0 up to 3. When the simulation depth/tier is 1, it evaluates the fault against all immediately adjacent protections, which will normally be enough for making sure the primary and backup protection is coordinated. However, the simulation area may need to be expanded beyond the depth of 1 to go over bus-ties, short lines, transformers. A typical value of simulation depth can vary among different short circuit software platforms and can be altered based on user preference, but 5 will be more than enough. It should be noticed that as the simulation depth increases, the simulation area can grow exponentially, which may create a burden on the computational capability of the computers. Some software platforms provide additional options to expand the simulation area, such as skipping over bus-ties and skipping over transformers without incrementing the simulation depth.

2) *Fault Location and Fault Types*

Software platforms provide several options for fault types, as well as offer flexibility in defining fault resistances. For a comprehensive study, it should include 1LG, 2LG, 3LG, and LTL fault types, and for both 0 and a user-defined fault resistance that best suit the evaluation needs. However, to optimize the simulation run-time, engineers may choose to simulate fewer fault types. The choice of fault types, as well as fault resistances, can be made based on the historical probability of occurrence of a given fault type in the system.

Fault location design is dependent on the network element type being faulted. Lines present a significant challenge in determining the ideal fault locations due to the variety of topologies that can be found. One of the main considerations in defining fault locations is uniform distribution. However, to optimize the simulation run-time, engineers may apply fewer faults in locations that are expected to result in different results while concentrating the faults in locations where coordination issues may happen due to the switching of active protective functions. Figure III-3 shows the typical fault locations to capture coordination issues due to the transition from Zone 1 distance to Zone 2 distance operation.

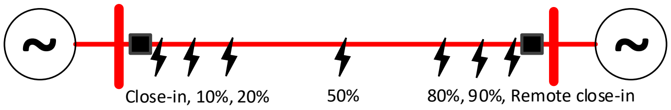

Figure III-3 Example of Fault Location Design

3) *Network Contingencies*

In addition to performing fault simulations in system normal network conditions, the fault types and fault locations are repeated under a variety of network contingencies. Ideally, the network contingencies, which the protection systems are designed for, should be tested during SEA-based simulations. The types of contingencies that are typically analyzed are N-1 network outages, including outaging of local and remote sources, mutually coupled lines, and line terminals (end open). In addition to the typical N-1 network outages, the following special contingencies can also be considered: outaging and grounding of mutually coupled lines and outaging of the generator while leaving the step-up transformer in service. It shall be noted that when a network element under study has only one source at the local or remote terminal, outaging that source may not be sufficient to study the N-1 contingency effect. Therefore, the simulation shall be designed to look beyond the single source and up to the next real bus with multiple sources to perform N-1 network outages.

4) *Protection System Contingencies*

In addition to network contingencies, protection system contingencies can also be included in SEA-based simulations. The most common type of protection system contingency is the outaging of redundant protective relay packages one at a time. This type of contingency is typically performed to assess if two redundant protection packages are performing similarly.

Outaging differential protection or teleprotection schemes is also feasible; however, it is less common. The primary benefit of performing differential and teleprotection scheme outages is to analyze protection system performance with and without them in service. However, if the main interest is to evaluate the worst-case scenario, then protection engineers may forego modeling them in the system.

It shall be noted that under specific circumstances, protection coordination is dependent upon the presence of differential or teleprotection schemes. In such cases, it is recommended to model these types of protection schemes and include them in the simulations; however, it will not be necessary to outage them.

5) *Coordination Time Interval (CTI)*

Coordination Time Interval (CTI) is the key to summarizing SEA results. To understand the CTI definition, it is important to understand the primary and backup protection categorization in the context of SEA. All protective devices that protect the network element under study are considered primary protection. In contrast, the protective devices for adjacent network elements are considered backup protection. When using SEA for performing coordination studies, a coordination time interval (CTI) is calculated for all backup protection elements that may potentially operate for the fault. It is defined as the difference in operation times of the backup protection and the fastest primary protection. Protection engineers should define the desired CTI as per the utility's protection philosophy, which can be used to flag any backup protection elements that have a lower CTI than the desired value.

C. *Reporting*

A typical SEA-based simulation may consist of several hundred fault scenarios resulting from the combination of various fault types, fault locations, network, and protection system contingencies. Each fault scenario may consist of several breaker operation events, where each event may contain several protective devices that can see the fault and are predicted to operate at different times. The raw results for all the fault scenarios are typically reported using the structure shown in *Figure III-4*.

Fault Scenario 1	**Event 0:** Fault Applied	• Report predicted operation time for all protective devices in the simulation area
	Event 1: Breaker Opens	• Report operation time for the protective device that resulted in breaker operation. • Report predicted operation time for all protective devices in the simulation area
	Event 2: Breaker Opens	• Similar report as event 1
	Events continue until the Last Event in which either the fault gets cleared or all protective devices drop out	
Fault scenarios continue until the last fault scenario is performed.		

Figure III-4 Report Structure for Simulation Raw Results

The raw report of one fault simulation may span over several pages, and for a complete study, the length of the report can grow very quickly. Therefore, the use of automation-based processing and analysis of raw results is essential to help facilitate the review of issues. This is discussed in more detail in Chapter 4.

D. *Application Types*

Stepped events analysis is primarily used for two types of studies – 1) Fault Clearing Time Analysis, and 2) Protection Coordination Evaluation. The type of studies impacts the choice over fault locations, as well as the protection modeling details. These are briefly discussed below:

1) A.Fault Clearing Time Analysis

Typical SEA-based fault clearing time study involves simulating a variety of fault scenarios as per the study requirements and recording the time at which the faults are cleared. When utilizing SEA for fault clearing time study, the scope of fault application is limited to the element under study, like that shown in Figure III-5. It must be ensured that an adequate set of protection devices are modeled that can clear the fault for the element under study.

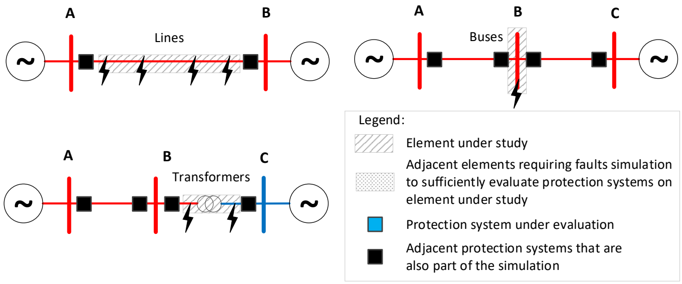

Figure III-5 Fault Application on Network Elements for Fault Clearing Time Analysis

2) Protection Coordination Evaluation

When utilizing SEA for protection coordination evaluation, the scope of fault application needs to be expanded to adjacent elements as well.

For protection coordination evaluation for a single element, the faults are applied on the element being evaluated, as well as all adjacent elements Figure III-6. This is required to ensure that the protection systems on the element being evaluated are coordinated with adjacent protection systems for faults on adjacent elements. The approach of utilizing SEA for protection coordination review is also commonly known in the industry as Wide-area Protection Coordination, as the analysis is based on protection operation response to a fault over a wide region of the network.

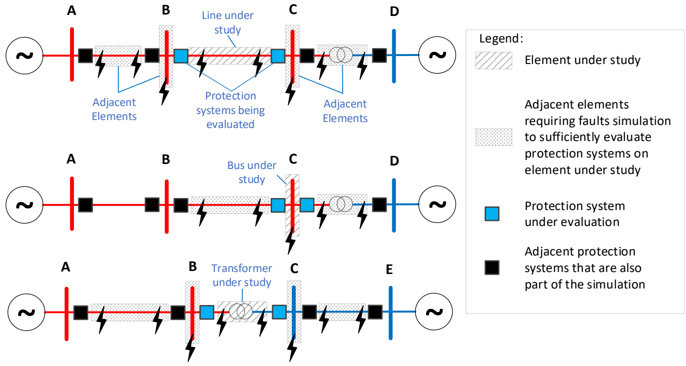

Figure III-6 Fault Application on Single Network Element for Protection Coordination Evaluation

Performing protection coordination evaluation for multiple elements across a region within a meshed network can be particularly advantageous, as the number of elements being subjected to faults is greatly optimized (Figure III-7).

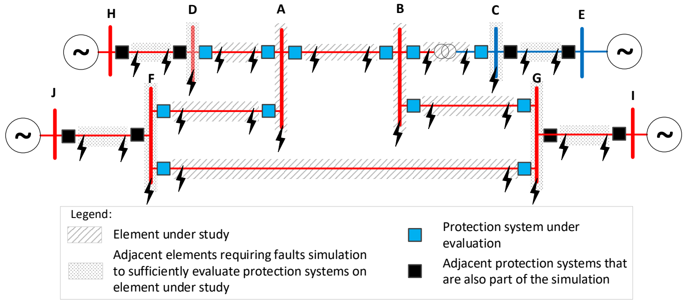

Figure III-7 Fault Application on Multiple Network Elements for Protection Coordination Evaluation

E. *Special Considerations for Line Simulations*

Designing SEA-based simulations for lines can be challenging due to the complex topological configurations that exist for lines, such as – multi-terminal lines, presence of load tap paths, presence of tapped paths with DERs. Additionally, there could be special cases, such as – super-bundled lines and series compensated lines, which require special considerations.

1) Fault locations on lines with complex topology

Fault locations are selected based on the general principle of uniform distribution across the line. The most common approach for applying faults on simple two-terminal lines is based on the percentage of positive sequence impedance of the line, i.e., faults are applied at set percentages across the line. The number of faults is typically determined based on utility protection philosophy and simulation duration preference. Traditionally, this approach has been adapted to lines with complex topologies by identifying all combinations of terminating bus pairs and then applying the faults uniformly across the different paths, as shown in Figure III-8. Although this method analyzes all the branches of a line in a systematic way, it can result in repetition of faults on the same branch at the expense of simplifying the fault selection input criteria.

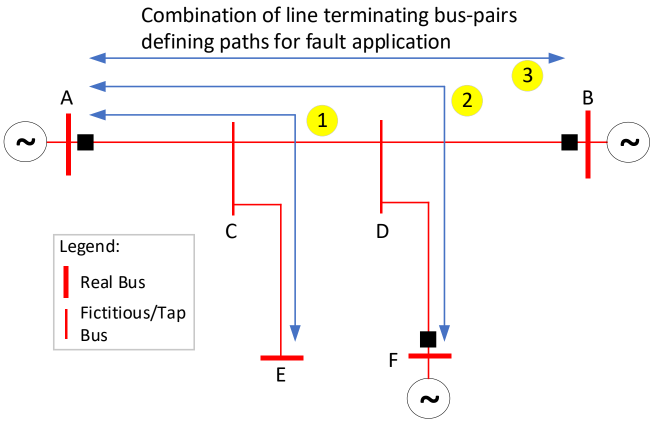

Figure III-8 Defining Paths for Fault Application Using Combination of Line Terminating Bus-pairs (Not Preferred Approach)

A practical way of addressing this challenge is to define a system of primary and lateral paths for a given line, as shown in Figure III-9. The number of set percentage faults applied on the main path is determined based on the utility criteria. Whereas, for the lateral paths, the number of faults is determined based on the relative impedance of the lateral paths compared to the main path. This method provides a systematic way of uniformly distributing the fault locations across multi-terminal lines without requiring detailed input from engineers before studying each line, which can be advantageous when performing automated system-wide studies.

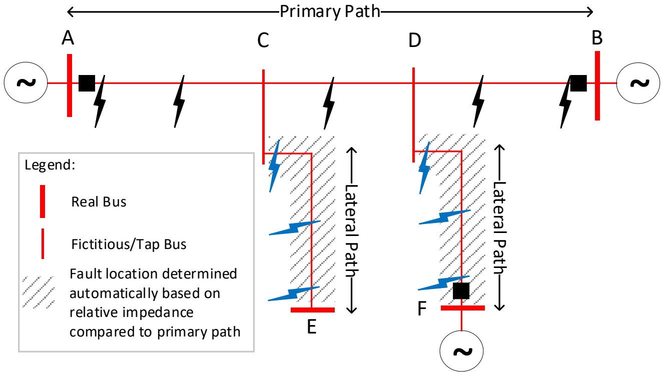

Figure III-9 Defining Primary and Lateral Paths for Optimized Fault Application

2) *Special consideration for super-bundled lines*

Super-bundled lines present unique challenges in determining the ideal fault locations for SEA. Depending upon utility preferences, super-bundled circuits may be modeled as an equivalent single circuit, which from the SEA perspective does not pose any greater challenges compared to typical lines. However, if super-bundled lines are modeled in detail and not as an equivalent single circuit, then additional consideration is required in defining the fault locations. Besides the general principle of uniformly distributing the fault locations across the lines, faults shall also be placed at the junction point. Special line end open contingencies should also be considered, as shown in Figure III-10.

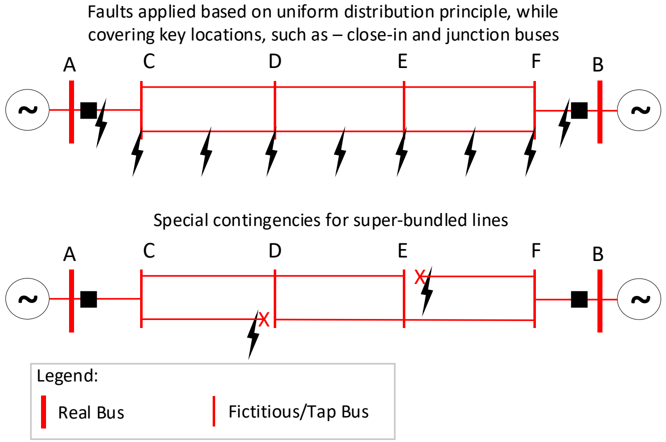

Figure III-10 Fault Application on Super-bundled Lines

3) *Special consideration for series-compensated lines*

The use of SEA-based simulations for series compensated lines is highly dependent on short circuit software platform capabilities. The protective relay operation on a series compensated line can be impacted by phenomena such as voltage inversion, current inversion, and inaccurate distance estimation. Protective relay manufacturers tackle these issues by employing advanced algorithms (such as memory polarization and Zone 1 blocking logic for external faults) [6].

Some protection simulation software platforms may provide detailed relay models with the ability to mimic advanced relay operation logic, such as providing different types of polarization options, including memory polarization. Additionally, they may allow modeling of metal oxide varistors (MOVs), which allows bypassing the series capacitors at high-current faults.

However, these features are not available across all simulation platforms and have not been widely reviewed or tested. They require further testing and analysis, and comparison of simulation results with real-life results.

Therefore, it is recommended to exclude series compensated lines from SEA review and evaluate protection system operation for such lines by using data obtained from Electromagnetic Transients Program (ATP-EMTP) or hardware in the loop analysis using Real Time Digital Simulator (RTDS) [6].

F. *Special Considerations for Transformer Simulations*

When performing system-wide coordination reviews, engineers can choose to skip performing SEA simulations on transformers in scenarios where dual redundant differential protection is present on the transformer. In this case, engineers may choose to only model the backup distance or overcurrent protection, if present. The backup distance and overcurrent protection being modeled on the transformer ensure that any coordination issues between them and the adjacent line protection are caught when faults are applied on lines using SEA. This approach can simplify the system-wide coordination studies by skipping transformer simulations and reduce the modeling burden by eliminating the need to model protection for them.

It shall be noted that there is still a need to ensure that line protection is operating slower than transformer protection for faults on the transformers. Since SEA is only recommended to be skipped for transformers with dual redundant protection, it can be assumed that only instantaneous or near-instantaneous over-reaching line protection elements will cause a miscoordination with differential protection on transformers. Such protection issues can also be caught through faults on other adjacent lines, and therefore, preventing the need to perform simulations on transformers.

However, if dual redundant differential protection is not present on transformers, then transformer simulations should be performed to ensure that the adjacent protection systems are coordinated in the absence of differential protection.

SEA implementation on transformers is limited by the short circuit software platform's ability to apply transformer faults. The commonly used simulation platforms in the industry only allow close-in faults on each of the terminals of the transformer and do not allow any through faults.

G. Special Considerations for Bus Simulations

Buses typically have differential protection schemes; therefore, there is only limited benefit of performing SEA-based simulations on buses for the effort involved in building and maintaining bus protection models. As described earlier, for the case of transformers with redundant differential protection, it can be assumed that only instantaneous or near-instantaneous over-reaching line or transformer protection elements will cause a miscoordination with bus differential protection. Such protection issues can also be caught through faults on other adjacent lines, and therefore, preventing the need to perform bus simulations.

IV. PROCESS AND DATA MANAGEMENT

As discussed in previous chapters, SEA-based simulations present significant challenges on process and data management. It not only requires complicated model preparation, but also generates large amounts of data due to the systematic approach of simulating a comprehensive set of fault scenarios. This chapter describes these challenges in more detail and discusses methods to mitigate them.

A. Model Preparation and Maintenance

The detailed short circuit network model of the power system is typically generated based on data from the asset management system and the geographical information system (GIS). Often only a positive-sequence network is maintained, which is required for planning studies. Negative-sequence and zero-sequence models are added to the positive-sequence for protection studies. The system model can be improved by adding more details such as detailed bus configurations and transposition of lines. However, the more details added to the system, the higher the burden of model maintenance. Utilities need to consider the trade-off between modeling effort and benefit on a case-by-case basis.

The protection model is primarily prepared using data from relay settings repositories. Additionally, single line diagrams and relay logic diagrams may be utilized for more accurate information such as CT/VT location and connection type, breakers being operated by the protective device, and teleprotection scheme details. However, for simplicity, this information is typically assumed based on a utility's protection philosophy and standards.

Most utilities have well-designed processes to maintain and update their short circuit network model. However, maintaining an up-to-date and accurate system-wide protection model to support the simulations can be a new and overwhelming requirement for most utilities. There are two fundamental challenges that the utilities are faced with:

- Keeping up with the constant evolution of the system
- Reducing human errors resulting from modeling process complexity

To resolve these challenges, utilities should invest in an automation-based protection modeling solution. This solution establishes a bridge between the relay settings repository and the short circuit software platform, and it has been successfully implemented at several utilities across the United States. Automation-based protection modeling is advantageous as it significantly reduces the model preparation time and human errors. With the reduced modeling effort, utilities may opt for creating more detailed models and benefit from more comprehensive studies [7].

To support automation-based protection modeling, utilities need to also establish good data governance processes across the key data repositories, such as asset management system, GIS, short circuit network, and relay settings repository.

It shall be noted that automation-based protection modeling can be prone to systemic errors resulting from deficiency/bugs in automation tools, deficiency/bugs in short circuit software platforms, and data integrity issues. Therefore, additional validation should be implemented to ensure high model quality. For example, unexpected operation of an element that is electrically far from the fault location or instantaneous operation of a timed element could be an indication of modeling errors. A combination of manual spot-checking and automated system-wide checks is encouraged.

B. Simulation Run Time

While SEA-based simulations provide an efficient method of analyzing protection behavior for a large number of fault scenarios, it does take considerably longer amount of time than a simple short circuit study, due to the added computational burden of protection operation. The analysis becomes more complicated with greater model detail, more fault scenarios and contingencies, and a more congested network.

A typical SEA-based study for a single element may take a few hours to finish. Reducing this time is not only preferred but often required as the studies need to be repeated to accommodate for:

- What-if scenarios,
- Testing new settings, and
- Fixing errors in the model or calculations.

A practical solution is to use dedicated servers to run simulation studies. This approach relieves engineer’s laptop computer resources and takes advantage of better hardware available to desktop and server computers.

In addition, the computation methodology used by short circuit software vendors to calculate short circuit and operation time of elements has a direct effect on simulation speed. The software vendors are constantly improving their software to increase its computation speed by using numerically efficient methods and technologies such as parallel processing. Utilities can influence vendors and expedite these enhancements through participation in their periodic users' group meetings.

Finally, adopting an optimized set of fault scenarios instead of the systematic brute force approach can help reduce the simulation run time. However, care shall be exercised in eliminating fault scenarios so that efficiency is achieved without sacrificing the accuracy of studies. For example, if there is high confidence that the redundant protection packages have identical settings, then protection package outages can be skipped.

C. Study Data Processing

As discussed earlier, the use of automated processing and analysis of SEA-based simulation raw results is essential to help facilitate the review of issues. The fundamental steps involved are described below:

- Analyzing Raw Results:

One of the first steps is to process the detailed primary and backup protection operation data for each fault scenario to identify potential miscoordination issues, i.e., misoperation or CTI violation issues.

- Condensing Raw Results:

The report of each element study includes a long list of fault scenarios and details of protective elements operation for each of them. However, only the uncommon cases of misoperations and serious CTI violations are important to be considered; the rest is the expected operation of the protection system and can be omitted when presenting data to the user.

- Re-organizing Results:

Simulation raw results are organized by fault scenarios. It is very common and entirely expected that issues with the same protective device could appear under many different fault scenarios, although in varying degrees of severity. Since engineers are primarily interested in protection issues and their appearance across the various faults scenarios, the raw results shall be re-organized by protective devices instead.

- Visualizing Results:

Both graphical and tabular visualization methods can be employed for SEA-based protection evaluation. The primary objective is to summarize the problematic fault locations, fault types, and contingencies for each miscoordinating protective device. The tabular method is easier to implement and helps with subsequent data aggregation across multiple studies for statistical analysis. The tabular method also forms the foundation for graphical visualization. The graphical method for visualization involves overlaying the issues on a simplified network drawing of the equipment under study and adjacent equipment, providing the reviewer the most straightforward view of the results.

V. CONCLUSION

Stepped-event Analysis (SEA) is a systematic and efficient method of protection evaluation and can be adapted to support a variety of compliance standards and programs requiring protection studies, such as NERC PRC-027, TPL-001, and PSPS program.

Although the concept is not new, protection evaluation using SEA has only recently seen an increase in adoption. However, several aspects of implementation still pose challenges to the industry, limiting the powerful tool from being fully utilized.

This paper discussed the practical considerations of implementing SEA, relating to modeling requirements, simulation design parameters, reporting, application types, model maintenance, and study data processing. The considerations discussed in the paper were based on recent implementation at two major US utilities, as well as experiences gathered by authors from several projects completed over the last decade.

The authors hope that the experiences shared provide them a reference to define a specific implementation strategy based on the needs of their organization, and encourage protection engineers to make it part of their protection review process.

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BIOGRAPHIES

Xinyang Dong, Principal Engineer, has been working as an engineer and consultant at Quanta Technology for over five years. She works primarily as a Project Manager on projects in data management and software design in the Power System Protection area. She has extensive experience in Protection Coordination studies using CAPE and ASPEN OneLiner. She developed several applications in CAPE and ASPEN to perform automatic protection coordination studies. She graduated with an M.S. in EE from North Carolina State University.

Ishwarjot Anand is a Senior Advisor at Quanta Technology, Markham, Canada, where he has worked since 2013. He received his MEng in Electrical Engineering from Ryerson University, Canada, and his BASc in Mechatronics and Robotics Engineering from the University of Toronto, Canada. He has expertise in computer-aided modeling and analysis of electrical power systems and protection systems for both transmission and distribution networks. He has led several protection engineering automation and data management projects, including automation for NERC PRC Standards Compliance. He has worked on large-scale wide-area protection coordination studies for AltaLink, Xcel Energy, and National Grid Saudi Arabia.

Mehrdad Chapariha (S'08–M'15) received B.Sc. and M.Sc. degrees in electrical engineering from Isfahan University of Technology, Isfahan, Iran, and Ph.D. degree in electrical and computer engineering from The University of British Columbia, Vancouver, BC, Canada, in 2006, 2009, and 2013, respectively. He is currently with Quanta Technology, Toronto, ON, Canada, as an Advisor, where he is working on the development of software solutions for fully automated and automation-assisted studying of power systems. His research interests include modeling and simulation of power systems, power systems data analytics, and autonomous power systems.

Saman Alaeddini received his MASc from Ryerson University and has been with Quanta Technology since 2009. He leads the engineering automation team at Quanta Technology that has developed many innovative software-based solutions for the power systems industry, particularly in the area of NERC compliance evaluation. Saman is a specialist in protection system modeling, database management and analysis, autonomous systems design, robotics, and industrial processes. He has been involved in wide-area protection projects for over 7000 transmission lines with 10 large electric utilities in North America and internationally.

Scott Hayes received his BSEEE from California State University, Sacramento in 1985. He started his career with Pacific Gas and Electric Company in 1984 as an intern. Since then he has held multiple positions in System Protection including supervisor, as well as Distribution Engineer, Transmission Operations Engineer, Supervising Electrical Technician, Supervising Engineer in Power Generation and is currently a Principal Protection Engineer focusing on standards, procedures, and quality. Scott has previously co-authored papers for the Western Protective Relay Conference, Georgia Tech Protective Relaying Conference, Texas A&M Conference for Protective Relay Engineers, CIGRE, TechCon Asia Pacific, CEATI Protection and Control Conference, North American Transmission Forum and Transmission and Distribution World Magazine. Topics include many aspects of protective relaying including Thermal Overload Relaying, Data Mining Relay Event Files, Effects of CCVT Ferroresonance on protective relays, PG&E's Wires Down Program and Ground Fault Neutralizers. Scott is a registered Professional Engineer in the state of California and has served as Chairman of the Sacramento Section of the IEEE Power Engineering Society and as chairman of the CEATI Protection and Control committee. He has served as a member of a NERC standard drafting team and is currently the Chairman of the North American Transmission Forum's System Protection Practices Group and Vice Chair of the IEEE PSRC WG45 group looking at Protection Methods to Reduce Wildfire Risks due to Transmission and Distribution Line.

Aaron Feathers is a Principal Engineer in System Protection Engineering at Pacific Gas and Electric Company, where he has been employed since 1992. He has 29 years of experience in the application of protective relaying and control systems on transmission systems. Aaron's current job responsibilities include wide area RAS support, NERC PRC compliance, and relay asset management. He has a BSEE degree from California State Polytechnic University, San Luis Obispo, and is a registered Professional Engineer in the State of California. He is also a member of IEEE and is on the Western Protective Relay Conference planning committee and participated in the NERC Protection System Maintenance Standard Drafting Team developing NERC Standard PRC-005-2 to PRC-005-6.

Chris Bolton is the manager of system protection automation and control engineering at SDG&E®, where he has worked since 2011. Bolton has held a variety of positions with the utility, including in substation engineering, capital projects, substation technical analysis and support, and system protection maintenance. Bolton graduated with a BSEE degree from California State Polytechnic University, Pomona, and is a licensed professional engineer in California.

Elliott Brown is a Senior Engineer at SDG&E® where he has worked since 2011. He has held a variety of positions with the utility, including Electric Transmission Design, Capitol Projects, Electric Distribution, System Protection Maintenance, and his current role as Senior Engineer in System Protection Automation and Control Engineering. He received his BSEE from California State University, Sacramento and is a licensed professional engineer in the state of California.