Lessons Learned Implementing a Wide-Area Coordination Program in Preparation for NERC PRC-027

Caitlin Short and Chris Byrne, P.E.
POWER Engineers, Inc.

Denis Bucco, P.E., Curtis Sanden, P.E., Art Torres, and Ed Wong, P.E.
Southern California Edison

Abstract -- **The effort associated with preparing existing systems to meet NERC PRC-027 varies with the size and complexity of the system and the state of the existing short circuit database. Wide-area coordination studies can be simple analyses or massive undertakings, depending on the end-user goals. An engineer implementing a system-wide program to align with future adoption of NERC PRC-027 will find both simple and complex cases. Through careful, schedule-driven planning and the definition of clear goals, the complexity, scope, and results are manageable for utilities.**

This paper will describe the approach to implementing a wide-area coordination program, challenges overcome, and benefits. It will also share lessons learned during the numerous, wide-area coordination projects completed within the program. The paper will detail how this program prepares Southern California Edison (SCE) for upcoming NERC PRC-027 implementation, cover the methods used to evaluate individual systems, and provide examples of real, challenging protection problems encountered.

I. Introduction

In early 2014, SCE concluded that numerous independent changes over the course of many years throughout several systems warranted a high-level look at protective relay settings, with the goal of identifying coordination gaps to improving overall reliability and guide the allocation of budgets for system improvements. SCE has completed pilot projects, developed standards, and scaled their approach to meet the needs of their extensive transmission and sub-transmission systems while overcoming many challenges.

Wide-area coordination studies are a great opportunity to examine a utility's existing protection system, but require accurate, detailed electrical models. Performing complex analyses while keeping efforts focused on in-scope equipment, meeting individual project schedules, and producing an easily understandable report is a challenging endeavor. Defining the level of detail and data necessary to build the electrical model, identifying system switching contingencies, and assigning risk levels to coordination violations that are found are all key components for a successful program.

II. NERC PRC-027

NERC Standard PRC-027 focuses on current-sensitive fault clearing protective elements that require coordination with other elements in a system. The goal of PRC-027 is to limit outages on the bulk electric system (BES) to the smallest area possible and for protective elements to operate in their intended sequence, thus preventing system instability and cascading outages. System protective elements should be set such that equipment is adequately protected by both primary and backup elements and these elements are time-staggered such that they operate in the correct sequence to isolate faulted equipment as quickly as possible with the fewest equipment outages.

The standard establishes criteria for which protective elements are evaluated and how often the coordination must be revisited. Fault currents change over time as system topologies change; thus, coordination between fault current sensitive elements is affected. Elements which fall under PRC-027 requirements are:

- *"21 – Distance if:*
  - *Infeed is used in determining reach (phase and ground distance), or*
  - *Zero-sequence mutual coupling is used in determining reach (ground distance).*
- *50 – Instantaneous overcurrent*
- *51 – AC inverse time overcurrent*
- *67 – AC directional overcurrent if used in a non-communication-aided protection scheme" [1]*

The standard outlines three requirements. Requirement R1 states that *"Each Transmission Owner, Generator Owner, and Distribution Provider shall establish a process for developing new and revised Protection System settings for BES Elements, such that the Protection Systems operate in the intended sequence during Faults." [1]* Requirement R2 outlines options for checking a system's continued compliance over time once an initial coordination study has been performed. An entity may:

- Option 1: Perform a coordination study every six years (or less).
- Option 2: Perform a short circuit study and compare fault currents to the previous study. A coordination study need only be performed if fault currents have changed by fifteen or more percent. This option requires that a baseline short circuit study has been established.

- Option 3: Use a combination of Option 1 and Option 2.

The third requirement is simply that once a process has been developed to satisfy Requirement R1, this process should be followed. Requiring entities to use a consistent approach across their system lowers the possibility for errors.

With this standard pending and the need to revisit coordination in their system due to equipment upgrades and topology changes, SCE recognized the opportunity to develop a process that would satisfy both needs.

III. SCE Program

SCE executed pilot projects to test and adjust their plan for establishing compliance across their subtransmission area and worked with POWER to develop a study process and report structure that establishes an initial coordinated subsystem. The report also documents short circuit currents for continued PRC-027 compliance via Option 2 of Requirement R2. Not all equipment located within these systems fall under BES classification, but SCE has developed a consistent approach to implement the analysis.

The scope of the wide-area coordination studies includes identifying elements that miscoordinate, have insufficient coordination time interval (CTI), or have pickups that are set below expected contingency line loading. A short circuit study is also performed to provide documentation for future PRC-027 compliance. The results of the short circuit study are used to check the sensitivity of overcurrent pickups versus fault current levels. To keep the scope of the study and schedule manageable, priority is placed on identifying and resolving coordination violations; if an element is set outside the range typically preferred by SCE, but causes no problems, the element is left as-is.

The schedule is developed around three distinct project milestones: model completion, first draft report completion with proposed settings changes for review, and the final report and settings. Project length ranges depending on the size of the subtransmission system, but with mindful planning and consistent project teams, data can be collected and ready for one subsystem as another study draws to a close. This approach, coupled with large project teams to perform parallel studies, allows SCE to move through their service area efficiently.

Each project is kicked off by a meeting between SCE and POWER to discuss anything unique about the system under scrutiny. Once the study is complete and a draft report submitted, a second meeting is held to discuss the findings and make any adjustments necessary before issuance of the final report. These meetings occur outside of regular project correspondence, and this face-to-face communication helps to keep consistency across the study areas as well as create an environment that encourages the exchange of ideas for continued improvements.

IV. Methodology

A. Establish Study Boundaries

The first hurdle for large scale coordination studies is to decide how service areas can be divided up into manageable portions to study individually. Each of SCE's subtransmission systems (66 kV or 115 kV) contains a main source substation providing the point-of-interconnection to the 220 kV or 500 kV transmission system and many satellite substations having transformers stepping down to the distribution level. These main and distribution transformers provide distinct boundaries within which to contain the wide-area coordination studies. The subtransmission systems are also isolated from each other, with only a few normally open connections to adjacent systems. An example 66 kV subsystem is shown in Figure 1.

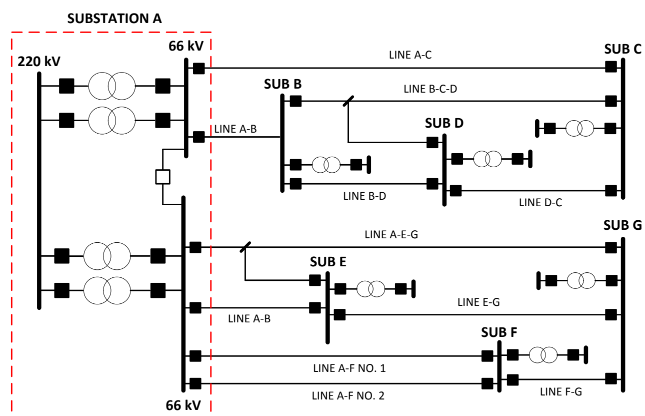

Figure 1: Example 66 kV Subsystem

B. Develop Criteria

Protective relay criteria are developed to establish bounds for acceptable coordination as well as guide in selecting new settings where problems are found. Guidelines for acceptable CTI between primary and backup elements, typical ranges for overcurrent pickups, preferred minimum fault current-to-pickup ratios, and reaches for distance elements, are all examples of guidelines set in the criteria document. The criteria dictate not only a preferred value, but also boundary conditions creating a range of what is still acceptable. Both IEEE standards [2] and SCE's typical protection philosophy are taken into account in the selection of criteria. NERC PRC-027 allows entities needing to comply to follow their own protection philosophies. NERC does not define a single criterion for what constitutes a coordinated protection system; they only require that protective elements operate in the intended sequence to minimize outages.

Most systems have multiple operating scenarios, usually a normal system and a contingency for the loss of a main source transformer. The criteria document states the scenarios that will be investigated in the study. Checking coordination under the operating scenarios that represent the maximum and minimum possible fault current cases will make clear any areas of vulnerability in the system. The system shown in Figure 1, for example, would have the coordination investigated with all four main transformers in Substation A in service with the 66 kV bus sectionalizing breaker open, as well as one transformer at Substation A removed from service and the bus sectionalizing breaker closed.

The overall goal is to bring the studied system back into a coordinated state with as few changes as possible. If elements are found to differ from the preferred criteria but pose no threats to proper coordination with other elements, the situations are noted but no changes are made.

C. Develop an Accurate Model

Before an accurate wide-area coordination or short circuit study can be performed, there must be an accurate impedance-based model of the system. Creating a system model that can be used for short circuit analyses falls directly within NERC PRC-027 Requirement R1, Option 2. Fault values recorded from the short circuit study establish the baseline.

Source equivalents (short circuit MVA and X/R ratios) of the higher voltage transmission system and connections to other subtransmission systems, transformers, and transmission lines must all be modeled accurately, as well as the existing protective relaying elements being studied. It is important that the model be put through a rigorous quality check before any studies proceed, as it is the foundation of all conclusions that will be drawn. Once an accurate model has been established, a short circuit study is performed followed by documentation of the state of coordination of the existing system settings.

At the conclusion of each study, SCE is in possession of both a model containing the subsystem's existing settings as well as one with any recommended settings changes included. Once new settings have been implemented, any field changes must be reflected in the recommended settings model. This model should be accurately maintained over time so it is ready to use each time NERC PRC-027 compliance must be revisited or new relay settings need to be developed.

D. Identify Coordination Violations

Coordination of each subsystem is analyzed one substation at a time. The existing relay settings must be tested for the multiple system operating scenarios laid out in the criteria, as well as for contingencies that may happen at that substation. Each relay's coordination is inspected both with all other lines and transformers in service and with a single piece of equipment removed. The majority of the subtransmission lines and transformers have differential protection, so overcurrent and distance protective elements are themselves a secondary layer of protection. Coordinating them for one piece of equipment taken out makes the system secure for the loss of a differential scheme coupled with loss of a single piece of equipment (defined as an N-2 contingency by SCE). If there is no primary high speed protection on the line, relay coordination is inspected with two pieces of equipment removed.

The existing coordination is documented in a spreadsheet organized by relay under headers for each substation (see an example layout in Table 1). Faults that present the worst-case coordination are documented with their fault type, contingency, and notes discussing the coordination with backup elements. To prevent duplication, coordination notes are only made next to the relay that should operate as the primary element.

Table 1: Example Coordination Spreadsheet

Zone of Protection	Fault	Contingency	Coordination Okay?	Notes
Substation A				
⋮	⋮	⋮	⋮	⋮
Substation C				
A_ 66KV_LINE	3PH Close-in	Line B-D Open	No	Miscoordination with Sub D, Line C Relay
	3PH Close-in	Line C-D Open	No	CTI violation with Sub B, Line C-D Relay
	3PH End-of-Line at A	System Normal	Yes	Relay coordinates with all backup elements.
	SLG Close-in	System Normal	Yes	Relay coordinates with all backup elements.
B_D_66KV_LINE	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮

E. Mitigate Coordination Issues

Once all coordination problems have been flagged, new settings are developed to bring the system back into coordination. POWER and SCE developed a single-page worksheet, referred to as a “case worksheet,” to present both the issues found and solutions in a coherent manner. Usually one case worksheet is developed per primary element that is involved in a violation. Cases contain three sections: the first shows the names and types of the relays involved with a simplified one-line diagram that is focused on the area under scrutiny, the second shows the existing settings with fault current and trip times for the faults that cause violations and a time-current curve (TCC) illustrating the violation found, and the third section repeats the information in the second but with new settings that are being recommended, updated element trip times, and a TCC showing that the violation has been resolved.

F. Write a Report

All conclusions from the study must then be put into cohesive report that progresses from a high level overview to a more detailed discussion of the analysis and results. Management should be able to read the initial overview and summary and see at a glance where the problems in a subsystem are and where they exist. The body of the report, coupled with tables and worksheets in the appendices, contain enough detail that a protection engineer can understand the process that was followed and reproduce any portion of the study if needed.

Coordination violations are shown in a table broken down by substation, with a risk level assigned to each one. The risk levels are described in Table 2 below.

Table 2: Coordination Violation Risk Classification

Classification	Example	Risk Level	Risk
Critical Mis-coordination	Relay will trip for out of zone faults before the faulted equipment’s primary protection can trip	High	Outage for equipment that is intact and unfaulted, in addition to faulted equipment
Mis-coordination	Relay will trip out of order or for out of zone faults before the faulted equipment’s primary protection can trip	Medium	Outage for equipment that is unfaulted, in addition to faulted equipment if primary protection fails to operate
CTI Violation	Relay will trip in the proper order for different system faults, but do not meet the SCE minimum CTI criteria	Low	CTI between protective devices may not leave enough time for the intended device to operate without the backup protective device operating as well

Time-delayed overcurrent and step-distance elements are secondary to line differential or communication-aided distance schemes. Miscoordination between such elements would only take place if the primary protection were out of service, so these violations are classified as a medium risk level. CTI violations are classified as low risk, because the backup elements still operate in the intended sequence; there simply is not a sufficient time stagger between them. Violations that are considered high risk are those that could cause false tripping, such as overcurrent pickups being set below expected load, or improperly set elements that would race the primary protection, such as instantaneous overcurrents.

A detailed set of appendices are attached that include the workbooks containing existing system settings and the short circuit study results, the spreadsheet documenting the existing system coordination, the cases that take a closer look at each violation and present a solution, and time-current curves for each element investigated.

This compilation of documents, coupled with test reports showing that all recommended changes have been implemented, contains all the information needed to show compliance with NERC PRC-027. It also establishes a baseline short circuit study for future compliance using Option 2.

V. Lessons Learned

Any type of coordination study will present its own set of unique obstacles. Tackling a service area as large as SCE’s is bound to have both non-technical and engineering challenges.

A. Model Complexity

Each subsystem contains a variety of relay technologies, protection schemes, and system topologies. How complex does a model need to be? For example, detailed double bus, double breaker substation models are accurate but time intensive to create. Accurate coordination can still be achieved through use of an equivalent single bus model. SCE chose to use simple bus models as a means of keeping the scope of each study manageable while meeting the data requirements of a coordination and short circuit analysis.

B. Communication

The SCE service area is divided into subsets overseen by separate lead engineers, and each area contains multiple subsystems. The general approach and documentation for each project is kept consistent by having all area leads (if possible) attend the meetings for each study, regardless of which area the subtransmission system is in. Changes to processes and documentation are discussed by all parties before being implemented and are communicated to all team members on the production side. A large part of the successes in past studies has been acknowledging that improvements can be made to the originally developed process. Taking time to identify and implement areas for improvement and communicating effectively throughout each project lifecycle is imperative.

Project leads and primary production engineers are established for both the utility and consultant side. A single-point-of-contact approach is not used. The production-level engineers are encouraged to work together and communicate frequently.

C. Documentation

Documentation itself is a challenge in this type of a study. The report may be read by a range of audiences, from executives to protection engineers. It is important that management be able to review the report and easily understand what the state of the system is, what problems exist, and the number of system changes that will be involved to resolve them. This information helps to clarify what system improvements should be prioritized when allocating budgets.

A protection engineer should find enough information in the body of the report and attached appendices that they can see the process that was followed in performing the study and data to support each violation found and solution created. However, with the vast number of elements under scrutiny and variables involved in a wide area coordination study, spreadsheets easily become bulky and overwhelmed by too much data. Creating separate documents for the different sections of the study (such as phase and ground short circuit, phase overcurrent coordination, ground overcurrent coordination, etc.) is a valid approach, but should be done with thoughtful design. Simplifying individual tables and spreadsheets by dividing them up can lead to information being repeated in multiple places, creating inefficiency in the work process, so a balance must be found.

The state of existing data presents further documentation challenges. The systems studied can contain a mix of several-decades-old electromechanical and modern microprocessor-based relays. Documentation can range from hand-written relay settings to electronic settings files stored in database management software. Teams need to be prepared for a thorough data gathering effort where it may not be possible to quickly retrieve existing digital settings from a database. Planning for the unknown data collection efforts means building an appropriate amount of time into the project schedule to gather, document, and thoroughly check the data used in the analysis.

D. Speed vs. Security

The balance of speed versus security is an engineering challenge that most protection engineers encounter when performing coordination studies. Systems may contain three-terminal lines connecting substations in multiple coordination loops. At times, the desired criteria for both speed and security cannot be met for these cases. The difference in fault current between the maximum and minimum contingencies can be great enough that a long total fault clearing time for the low current contingency must be accepted to prevent miscoordination at the maximum fault current. Priority is given to security over speed to meet coordination requirements.

VI. Conclusions

As the program evolves, new challenges continue to present themselves, but the process developed has proven to be an effective means of tackling such a large service area. Not only does each subtransmission system become coordinated and compliant with NERC PRC-027, but additional benefits are achieved along the way.

Conveniently documenting all existing settings in one place, along with coordination study results, provides an aid to utilities for identifying and prioritizing areas of vulnerability. Coordination studies help to identify which pieces of equipment can no longer meet the protection requirements of speed, sensitivity, and security and need to be replaced.

The task of NERC PRC-027 compliance can seem a daunting one. However, NERC PRC-027 does not require a compliance sheet for each protective device. With careful planning and effective communication, typical system studies can be adapted to serve both the utility's compliance needs and aid them in understanding the state of their systems.

VII. References

[1] NERC, *PRC-027 Coordination of Protection Systems for Performance During Faults,* National Electric Reliability Council, Draft 6, 2015

[2] IEEE, *Std. 242-2001: IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems*, The Institute of Electrical and Electronics Engineers, New York, 1999, ISBN 0-471-85392-5.

VIII. Biographies

Caitlin Short is in her fourth year at POWER Engineers working in the SCADA and Analytical Services group. Her work includes several types of electrical system studies including power system analysis, protective relaying, wide-area coordination studies, transmission line design, and arc flash studies. Caitlin received her B.S. in electrical engineering from the University of Idaho.

Chris Byrne, P.E. joined POWER Engineers in 2007. He is a member of the SCADA and Analytical Services group where he performs a variety of electrical system studies for power transmission and distribution projects. He has a background in power system analysis, protective relaying, wide-area coordination studies, transmission line design, reactive compensation studies, and arc flash studies. Chris holds a B.S. in electrical engineering from the University of Idaho and is a registered professional engineer in Maine.

Denis Bucco, P.E. is a protection supervisor in the engineering department of Southern California Edison. He received his BSEE from the Universidad de Carabobo in 2000 and his MSEE with honors from California State University, Los Angeles in 2003. He joined Southern California Edison as a protection engineer in 2003. He is a senior protection engineer with 13 years of experience working in the electric utility industry. He is a registered professional engineer in the state of California and a WPRC committee member.

Curtis Sanden, P.E. is a senior protection engineer in the engineering department of Southern California Edison. He received his BSEE from California State Polytechnic University, Pomona in 1991. He joined Southern California Edison as a protection engineer in 1992 and has 24 years of experience working in the transmission and generation protection utility industry. He is a registered professional engineer in the state of California and a member of the WECC Relay Work Group.

Art Torres is a protection supervisor in the engineering department of Southern California Edison. He received his BSEE from California State University, Los Angeles in 1999. He joined Southern California Edison as a protection engineer in 1999. He is a senior protection engineer with 17 years of experience working in the electric utility industry.

Ed Wong, P.E. is a protection supervisor in the engineering department of Southern California Edison. He received his BSEE from California State University, Los Angeles in 1991. He joined Southern California Edison as a protection engineer in 1991. He is a senior protection engineer with 25 years of experience working in the electric utility industry. He is a registered professional engineer in the state of California.