Comparison of Risk Assessment Approaches in Wide Area Protection Coordination

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1. Introduction

The growing complexity of modern protection and control systems poses a great challenge to power transmission utilities in terms of maintaining and upgrading their network. Automated wide area protection coordination (WAPC) study is a tool that allows utilities to analyze protection coordination of all adjacent protection systems in detail and in a relatively short period of time compared to traditional methods of coordination analysis. Given the large scope of such studies, the results obtained can be overwhelming for a utility to analyze and/or to implement the recommendations in a reasonable period of time. Hence, utilities have to assess the risks associated with issues reported in the study and prioritize them to meet their specific requirements. This paper presents two different approaches adopted by two utilities from North America, namely Xcel Energy and AltaLink.

Xcel Energy is a major electric and natural gas company in the United States with operations in eight Midwestern and Western states. Its electricity operations serve 3.5 million customers, and assets include approximately 1,200 substations, 87,000 miles of transmission lines, and 193,000 miles of distribution lines. Xcel also owns approximately 440 generating units (with a diverse portfolio) totaling 16,785MW [1].

AltaLink is a major transmission facility owner in Canada that owns more than half of Alberta's transmission grid and serves 85% of its population. It is responsible for the maintenance and operation of approximately 12,500 km of transmission lines and 280 substations in Alberta operating at system voltages from 69kV to 500kV. AltaLink owns and maintains roughly 15,000 protective relays in its system.

2. Automated Wide Area Protection Coordination Studies

Automated WAPC study evaluates the protection system of the entire or a portion of transmission network of a utility. The WAPC study is a type of protection audit. The different parts of the audit process are captured in figure 1 and are described below in detail.

Standards and Guidelines: The utility's own standards and practices, combined with requirements and standards mandated by regulatory bodies and/or independent system operators to guide the protection audit process. These practices might define a minimum acceptable coordination margin between primary and backup protective relays, or might specify acceptable limits for sensitivity of distance and overcurrent protection elements. All such requirements are first documented very clearly and form the basis of the entire study process.

Protection Software Platform: The protection software platform is the computer-based model of the utility's power system, including the protection. This model must be reasonably accurate and complete, and must be maintained so that changes in the actual system (both short circuit network and protection model) are captured in the model. Therefore, the utility needs a well-defined and documented procedure to keep this model up-to-date.

Macros: Macros are automated batch processes that run within the framework of the protection software platform. There are three main types of macros that are used in the protection audit process, namely, Sensitivity, Coordination and Reliability macros. The sensitivity macro performs automated relay setting checks against the criteria set by the utility. The reliability macro on the other hand, is designed to evaluate the protection system for compliance with regulatory requirements, such as, Transmission Relay Loadability (PRC 023) and Generator Relay Loadability (PRC 025) standards developed and enforced by the North American Electric Reliability Corporation (NERC), which is a not-for-profit international regulatory authority whose mission is to assure the reliability of the bulk power system in North America [2]. The WAPC study mainly uses the coordination macro that simulates a wide range of fault types, fault locations and system contingencies and assesses the behavior of protection devices one to two substations away from the fault. The batch process approach's greatest advantage is its ability to perform large scale studies that are impossible to undertake in a manual fashion. Further, macros allow the utility to periodically review the protection system. Reports produced by the macro can be used to demonstrate compliance with utility practices and/or regulatory requirements.

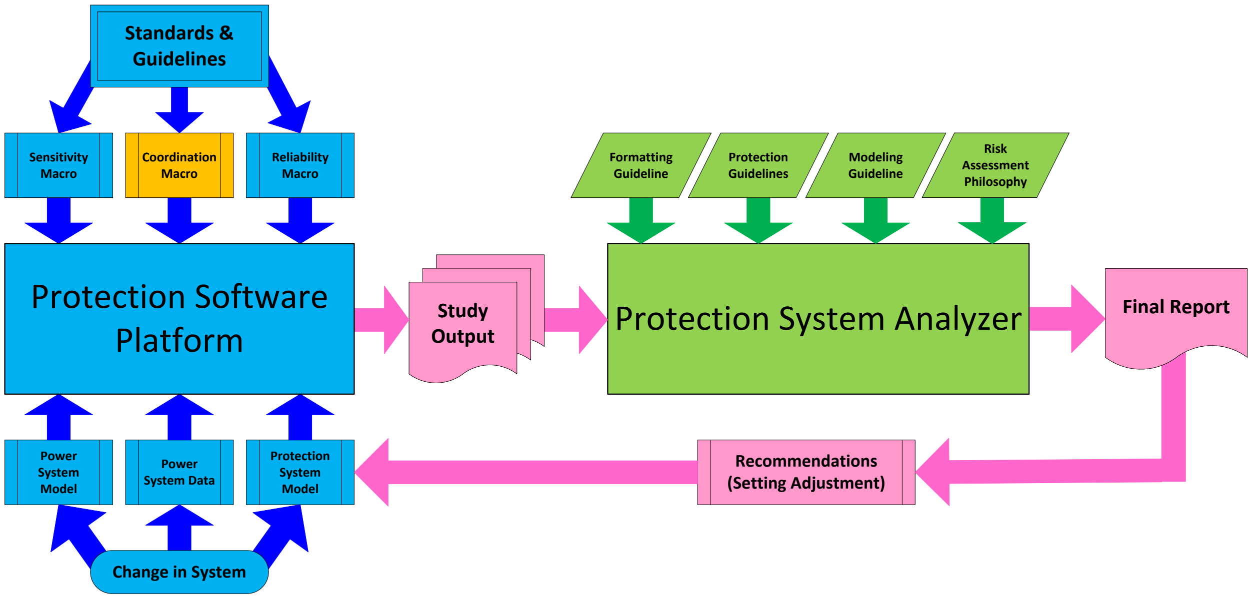

Figure 1: Protection Audit Process

Study Output and Protection System Analyzer: The macros, running on the protection software platform generate a large amount of study output. These take the form of Rich Text Format (RTF) files, color-coded with detailed sequence-of-events output that demonstrate how every fault that was applied on the system was cleared. While this output is useful, it is difficult for an engineer to analyze and provide setting change recommendations. Therefore, the study output is processed by the Protection System Analyzer to create condensed spreadsheets that help focus the relay engineer's attention on the most severe problems identified that need to be addressed.

The power system analyzer function is a combination of automated and manual effort. It is automated in the sense that the raw study output from the macros is automatically processed to create the condensed spreadsheets. Further, based on utility guidelines and criteria, the problems found are also ranked on the basis of severity – highest risk (must mitigate) to lowest risk (acceptable). At this point, the protection engineer can focus on the highest risk issues and determine the mitigating action to be taken. This action can be a relay setting change, a relay package upgrade, or a protection system upgrade (addition of a teleprotection scheme). Once the protection engineer's recommendations are in place, a Final Report listing all the recommendations and upgrades is created.

Recommendations: All setting change recommendations are then incorporated into the protection software platform. The software platform allows for multiple relay setting groups to be created, so that "before" and "after" comparisons can be easily made. The macros explained above can now be re-run to assess the impact of the recommendations.

A study of this magnitude has multiple advantages, such as allowing utilities to proactively comply with regulations and reliability standards that could be introduced in near future. Also, a by-product of the investment is development of automation tools that can be used for making day to day protection analysis more efficient. Furthermore, utilities establish greater confidence in their system model as wide area coordination studies require detailed modeling/verification of primary network data (such as transformers, generators, shunts and line data) and the protection system.

In 2013 Xcel Energy conducted a study of protection systems installed on approximately 1000 bulk power (>100kV) transmission lines in three operational areas of its system and is beginning the process to review the findings of the study and building recommendations for upgrades. One of the key motivations for undertaking such a large scale study was to explore the full potential of automated WAPC studies that improve the protection engineer's confidence by applying a much larger set of contingencies putting the protection settings through a much more stringent test. The automation of the protection study relieves the protection engineer of the tedium of manually applying contingencies, and faults, and focuses their attention on the settings issues that have been uncovered.

Another key motivating factor was Xcel's participation in the CAPX2020 program, which is a joint initiative of 11 transmission owning utilities in Minnesota, North Dakota, South Dakota, and Wisconsin formed to upgrade and expand the electric transmission grid to ensure continued reliable and affordable service [3]. The CapX2020 projects provide needed transmission capacity to support new generation outlet, including renewable energy [3]. This is the largest development of new transmission in the upper Midwest United States in nearly 40 years [3]. The new transmission lines under this program are projected to cost more than $2 billion and cover nearly 800 miles [3]. These and other planned upgrades are expected to create significant changes in the system fault currents. For instance, it may lead to over tripping of instantaneous protective elements and other types of miscoordinations. Automated protection system verification helps ease the pressure on engineering teams who not only have to create new protective relay settings for the CAPX2020 project, but also validate coordination on all existing transmission network protection schemes.

In 2014 AltaLink also conducted a similar study with a complete review of the findings on approximately 600 transmission lines (>69kv) and on 300 selected transformers and 120 selected buses. The main motivation was due to the large number of new assets that have been added to the power system in recent years and that are planned over the next few years. AltaLink's transmission system is currently evolving significantly, and because project protection studies are typically focused only on the immediate facilities that are impacted by the project, the overall cumulative impact of all of the projects to the protection systems becomes increasingly uncertain. Without performing area coordination studies, the risk of having a protection misoperation increases proportionally as more and more additions and upgrades are completed. Also, the large number of projects that are underway increases the amount of planned outages to the system which further increases both the chance of having a protection misoperation and the impact of misoperations to the system/customers. Performing the area coordination study ensures that AltaLink is better able to manage the risks that exist in the protection system as assets are changed or added to the power system.

3. Need for Risk Assessment and Prioritization

The extent of data produced in wide area coordination studies is very large. Each line coordination study could simulate an average of 600 fault scenarios, and each bus or transformer coordination study could simulate an average of 150 fault scenarios. Results from each line study contain approximately 1500 pages of data with an average of 3000 sequential events. The data obtained for transformers and bus studies is of similar order. When multiplied with the hundreds of lines, transformers and buses that are studied, the results quickly become overwhelming. Reviewing the results and implementing the recommendations in a reasonable time-frame becomes an enormous challenge due to a limited number of resources being available. Therefore, assessment of risk associated with issues reported in the study, and prioritization of them, is a critical step for utilities before using the results in a meaningful way and to formulate a strategy to maximize the impact of any investments in resolving the issues.

Also, instead of just being a secondary process performed at the end of the coordination study, in case of AltaLink, risk assessment is one of the primary objectives. The WAPC study was an opportunity for AltaLink to improve its asset planning for P&C equipment replacements/upgrades by quantitatively prioritizing which upgrades would provide the most value from a system safety and reliability perspective. By performing a detailed risk assessment and prioritization, protection replacement/upgrade programs can be optimized to ensure that they are mitigating the most risk to the system. The risk scoring system also facilitated the integration of the work that was required to fix the vulnerabilities from the study, with other planned and corrective maintenance work.

4. Comparison of Risk Assessment and Prioritization Philosophies

Risk assessment philosophy of each utility is developed to meet the specific characteristics of the network they own and connect with. Therefore, both AltaLink and Xcel have their unique perspective on how to assess risk and prioritize the issues for further actions.

The general approach that is central to both AltaLink and Xcel is that of Probabilistic Risk Assessment, whereby risk associated with a given protection vulnerability discovered during the study is the product of the probability of a miscoordination occurring due to the vulnerability, and the consequence to the system if it occurred. However, the way probability and consequence are assessed and incorporated into the final score is very different between the two.

AltaLink's Risk Assessment Philosophy

The goal of AltaLink's risk assessment methodology was to quantify the relative risk that each protection vulnerability presented to the safe and reliable operation of the system. Having the relative probability and consequence scores for each vulnerability enables asset planners to make more informed decisions on where to focus efforts in order to mitigate the most amount of risk to the system.

AltaLink's methodology can be broadly divided into a two-step process. The first step is to calculate risk scores for each issue found in the study and second step is to re-assign the risk scores to the protective element that is the root cause of the issue.

For a given study, the basic entity to which the risk scores are first assigned is the miscoordinating protection element, such as a distance or an overcurrent protection element within a protective device. The risk scores can then be summed together in a hierarchical manner to obtain total risk associated with other system entities such as protection devices, protection zones, substations or geographical regions as shown in figure 2:

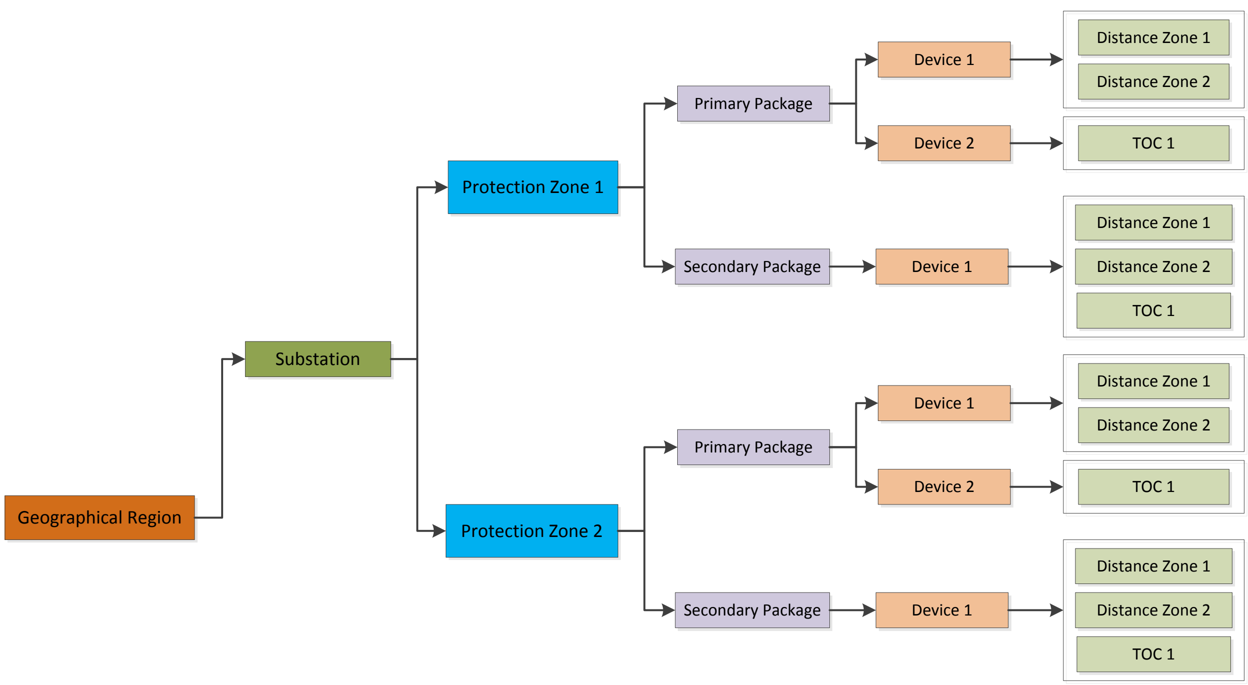

Figure 2: Protection System Hierarchy

The risk equation below provides an overview of AltaLink's risk calculation methodology.

CTI Factor = f(Coordination Time Interval of an issue)

Consequence = f (Impact to Bulk Electric System, Load Loss (MW), Safety and Environmental Impact)

$$\text{Total Risk associated with protection element} = \sum_{\substack{\text{All Simulation cases}\\ \text{where the issue}\\ \text{has been found}}} \text{CTI Factor} \times \text{Probability}_{\text{of a case}} \times \text{Consequence}_{\text{of a case}}$$

Probability = f (Fault Probability, Contingency)

In the above risk equation, each simulation case is a unique combination of fault type, fault location and a forced system outage. The risk associated with a protection element is calculated by summing the product of probability and consequence for each simulation case where an issue has been discovered with the respective protection element.

The probability associated with a simulation case is a function of the fault probability and the system contingency applied during the simulation. The fault probability is determined using AltaLink's historical forced outage statistics for the studied equipment (i.e. a line, bus or transformer), which was provided in the form of faults/100km/year for lines, and as average number of faults/equipment/year for all buses and transformers. If a system contingency (such as a system outage or protection outage) is applied during a simulation, then the probability value is adjusted by multiplying with a factor of 0.001 to account for the lower probability of having a fault and a planned system or protection outage at the same time.

The consequence associated with a simulation case is a function of the impact it would have on the Bulk Electric System (BES), the amount of customer load that would be interrupted, and the impact on safety and environment. Each system equipment (lines, buses and transformers) had a pre-defined rating on a scale of 1 to 5, for each of the three consequence parameters, where higher rating implies a more adverse impact to the safe and reliable operation of the system. The total impact was calculated by first determining the list of lines, buses and transformers that are outaged as a result of the applied fault, and then combining their individual ratings. Automation plays a very important role in providing the information required to determine the consequence score as the coordination macro reports all outages, which are then related back to ratings through the protection system analyzer. For a system wide study, the process to accurately determine the consequence score can quickly become very tedious; therefore, the use of automation is imperative.

The product of probability and consequence is also adjusted based on whether the element misoperated or whether it only had a coordination time interval (CTI) violation i.e. the CTI between the misoperating element and the fastest primary protection element is below the minimum threshold set by AltaLink. The threshold for the CTI violation is set differently by each utility depending upon their protection system design and risk tolerance. As lower CTI values indicate a higher probability of actual misoperation, the CTI factor is assigned a value that gradually increases from 0 to 1, as the CTI value decreases from the minimum threshold to the point of misoperation.

The next step in the process is to re-assign the risk scores to the root cause protection deficiency. This is required if the element originally reported as an issue is misbehaving due to a protection deficiency at another location in the system. For instance, an inadequate primary protection design may result in the backup protection to be reported as a misoperation. This is only made possible through a detailed review of all the issues found in the study and requires a great amount of time and effort as it is a manual process undertaken by a protection engineer.

Xcel Energy's Risk Assessment Philosophy

Xcel Energy's approach is a hybrid of quantitative and qualitative analysis. The quantitative analysis is relatively simplified, and requires less time and effort when compared to AltaLink's methodology. It is followed by a thorough qualitative analysis of the results before a plan can be defined to mitigate the highest protection risks first. The goal of Xcel's approach is to locate the substations with most number of protection issues and with the greatest combined risk. The quantitative analysis is similar to the process described earlier for AltaLink; however, there are major differences in how the probability and consequence factors are determined. The risk equation below provides an overview of Xcel Energy's risk calculation methodology.

Probability = f (Fault Type, Contingency, Coordination Time Interval of an issue)

$$\text{Total Risk associated with protection element} = \sum_{\text{8 worst issues, 1 each for 8 key categories}} \text{Probability} \times \text{Consequence}$$

Consequence = f (kV rating of line under study)

Risk score are calculated for each miscoordinating protection element reported in the study. The total risk score is the sum of the products of probability and consequence of the eight worst instances of protection miscoordinations. These instances are selected from eight pre-defined miscoordination categories, one from each category. These categories are shown in figure 3:

Category	Type of Miscoordination	System Contingency	Type of Fault
1	Misoperation	System Normal	Bolted Fault (SLG, DLG, LTL, TPH)
2	CTI Violation	System Normal	Bolted Fault (SLG, DLG, LTL, TPH)
3	Misoperation	N-1 Contigency	Bolted Fault (SLG, DLG, LTL, TPH)
4	CTI Violation	N-1 Contigency	Bolted Fault (SLG, DLG, LTL, TPH)
5	Misoperation	System Normal	Resistive Fault (SLG-5ohm, DLG-5ohm)
6	CTI Violation	System Normal	Resistive Fault (SLG-5ohm, DLG-5ohm)
7	Misoperation	N-1 Contigency	Resistive Fault (SLG-5ohm, DLG-5ohm)
8	CTI Violation	N-1 Contigency	Resistive Fault (SLG-5ohm, DLG-5ohm)

Figure 3: Miscoordination Categories

The probability of occurrence of a miscoordination for a specific category is determined by assigning pre-defined probability scores to each of the eight categories and then adjusting the scores based on the type of miscoordination i.e. a misoperation or a CTI violation. A table similar to the one shown in figure 4 is created to show the probability score for each category and how they overlap. Since the risk analysis is relative in nature, the values assigned to each category are kept flexible and can be altered to suit Xcel Energy preferences in terms of giving additional weighting to certain types of miscoordinations. For example, in figure 4, misoperations found on bolted faults for both system normal and N-1 contingency studies, are given a much higher score compared to the CTI violations close to 0. Also, the scores for CTI violations are decreased linearly as the CTI value increases to the minimum threshold set in the study.

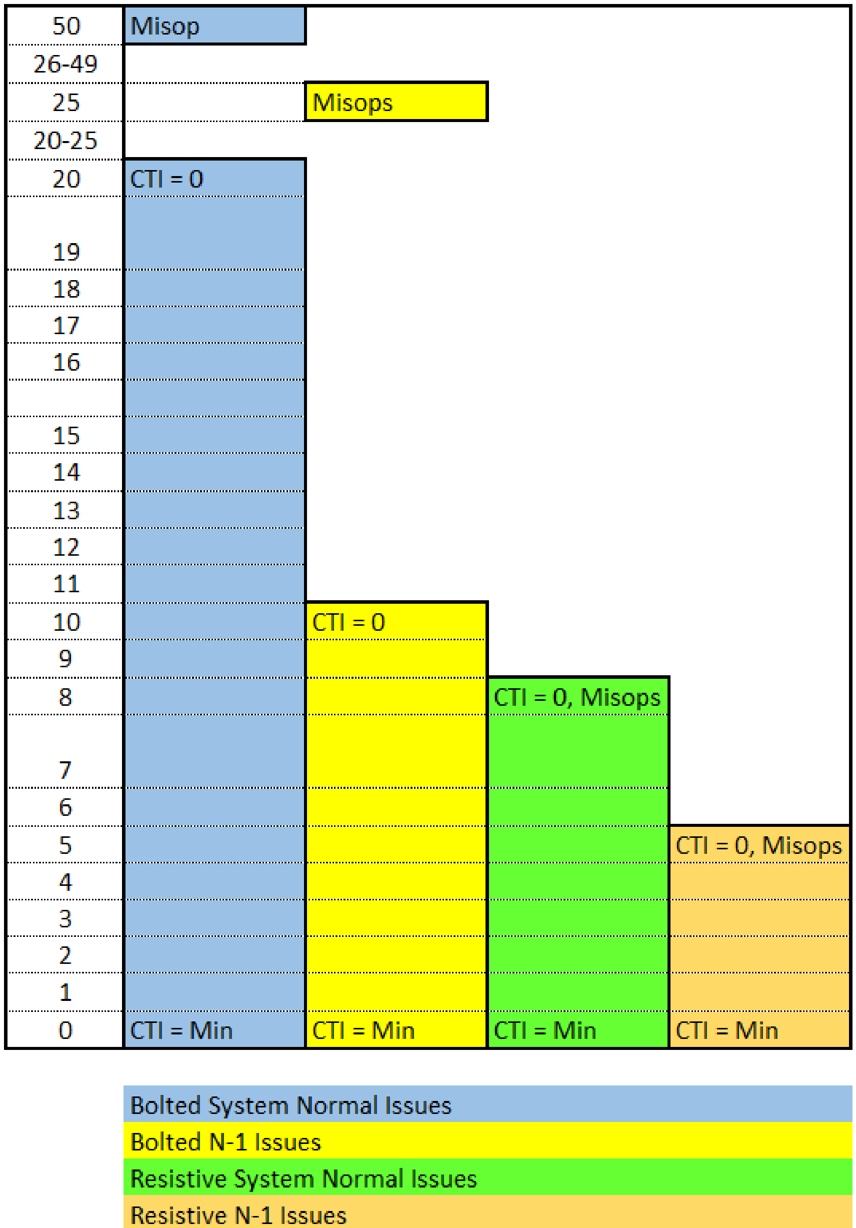

Figure 4: Example of Xcel Energy's Probability Scoring Chart

The consequence scores are based on the kV rating of the transmission line where the miscoordination is detected. This is an indirect but an effective method of determining the possible consequence of a miscoordination as it helps to highlight the issue around the transmission lines that carry higher loads than the rest of the system.

Once, the total risk score for each miscoordinating protection element is quantified, they are finally summed together in a hierarchical manner (as shown in figure 2) to obtain the total risk associated with the substations where they reside.

In the qualitative analysis that follows, the risk scores from all the studies are combined to create a heat map of protection deficiencies for all substations under review. The heat map displays the substations with a high, medium or low risk tags and allows for further evaluation based on qualitative parameters such as, impact to bulk electric system equipment that is critical to system stability, planned system upgrades, and proximity to important infrastructure.

Once the highest risk substation is selected, the protection zones that have the highest risk within that substation are identified and reviewed first. All other violations that may exist at the selected substation are also reviewed at the same time. Any violations on the adjacent line, due to the study on the highest risk protection zones, are also reviewed as part of the process at this time.

Any settings changes identified for the protection zones reviewed above are then scheduled and applied in the field via Xcel Energy's relay issuing process. The process may be repeated for the next substation in the region with the highest risk so as to complete the entire region. This approach of targeting issues from the same region at the same time minimizes future interruptions in the same area and is more cost effective.

Xcel is the initial stages of the review process; the process will be evaluated and changes made as seen fit to address challenges. Once this process of data review has been sufficiently tested out, Xcel may use this process to develop and enhance asset replacement strategies.

5. Conclusion

The automated WAPC study evaluates the protection system of the entire transmission network of a utility, or a portion of it. By automating the actual process of applying faults and system contingencies, this approach relieves the protection engineer from the tedium of manually performing the studies.

The primary benefit of a WAPC study is to mitigate the risks of wide area disturbances due to latent protection settings deficiencies. With rapid and widespread capital investment in new infrastructure, protection engineers neither have the time, nor the resources to thoroughly evaluate protection settings by thoroughly challenging them before deployment. A comprehensive automated study will therefore help improve system reliability.

The macros running on the protection software platform generate a large amount of study output. These take the form of Rich Text Format (RTF) files, color-coded with detailed sequence-of-events output that demonstrate how every fault that was applied on the system was cleared. While this output is useful, it is difficult for a human being to analyze and provide setting change recommendations. Therefore, the study output is processed by the Protection System Analyzer, to create condensed spreadsheets that help focus the relay engineer's attention on the most severe problems that must be mitigated.

A study of this magnitude has multiple advantages, such as allowing utilities to proactively comply with regulations and reliability standards that could be introduced in near the future. Also, a by-product of the investment is the development of automation tools that can be used for making day to day protection analysis more efficient. Furthermore, utilities establish greater confidence in their system model as wide area coordination studies require detailed modeling/verification of primary network data

Xcel's and AltaLink's risk assessment philosophies are different in many aspects. One of the key points of differentiation is the final system entity to which the risk scores are assigned. Xcel assigns risk scores to the protective elements that show up as miscoordination in the study output and prioritizes which protection zones to review first, whereas AltaLink assigns the risk scores to the root cause protection vulnerability, which requires a complete review of all the studies before the risk analysis can be completed. This difference speaks to the way both utilities intend to use the data in the immediate future. Xcel intends to use the risk data to resolve all protection issues at or around high risk substations. AltaLink on the other hand, intends to use the data to improve their protection asset strategy by identifying high risk protection terminals/zones, therefore it needs to assign the risk to the asset that needs to be updated or replaced.

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