American Electric Power's Experience with Protection System Misoperations and Improvements

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***Abstract*— This paper will share American Electric Power's (AEP) experience with protection system misoperations and their approach in leveraging automation, industry best practices, and incorporating internal lessons learned into key engineering processes in attempt to reduce AEP's total number of protection system misoperations.**

I. Introduction

AEP has one of the largest transmission systems in the United States (more than 40,000 miles of network that includes extra high voltage transmission lines up to 765kV and complexities from series compensated lines all the way to phase shifting transformers (PST)) and grid reliability is very important to AEP and its regional compliance entities. Since today's society is so heavily dependent on electrical power system infrastructure, it is crucial that AEP has the highest possible reliability for its many millions of customers. Protection system misoperations can come in a wide variety and their specific causes are often hard to fully determine. This paper will take a deep dive into trending protection system misoperations that AEP has experienced on its grid and highlight key improvements that AEP's Protection and Control Engineering (PCE) department has developed to mitigate protection system misoperations in the areas of relay settings, logic, design errors, and relay malfunctions.

Over the years, transmission system protection designs have evolved and have thus become inherently more complex with the new generation of microprocessor based protective relays, wide spread grid integration of Flexible AC Transmission System (FACTS) devices, and the addition of decentralized inverter based renewable generation (wind and solar) to the grid. This coupled with a relatively younger protection and control experience level within the industry adds to the complexity. This complexity can lead to protection system misoperations (a key risk to the Bulk Electric System's (BES) reliability) in the absence of well thought out protection and control design standards, accurate short circuit system models, standardized tools/training for developing protective relay settings, and thorough peer reviews of the complete design and relay settings.

The keys to addressing these issues and minimizing protection system misoperations is to leverage automation, embrace industry best practices, simplify protection and control schemes, and incorporate lessons learned from system misoperations into key engineering processes so that the same mistakes are not made in the future. These efforts can help achieve zero system misoperations caused by incorrect relay settings, logic, and design errors.

II. Reviewing Operations and Determining Misoperations

AEP reviews all breaker operations shortly after they occur. A team from Transmission Field Services Protection and Control (TFS P&C) takes the first stab at reviewing the operation and tries to determine if it is a correct operation or a misoperation. They perform this task by first collecting the event data from field personnel, dispatchers, and relay oscillography. During their review, they determine where the fault was and if the associated protection zone operated as intended exclusively to clear the fault.

Once an operation has been determined to be a misoperation by TFS P&C, they will then introduce the misoperation to the PCE department. There is a group of regional PCE technical engineers that meet and collaboratively determine the cause of the misoperation. The group draws on a lot of experienced individuals that are located throughout the AEP service territory. This approach helps ensure that the correct root cause is identified. One of the most important steps to reducing misoperations is to first correctly identify the true root cause so that then corrective actions and improvements can later follow. AEP performs this task in a group setting so that many different viewpoints and years of technical experience can be leveraged. This group setting allows for all regions of AEP to be plugged into the misoperation cause and allows for the different regional engineers to bring back and share this information with their specific regional teams in attempt to raise awareness.

III. Corrective Actions Plans

Once PCE has officially determined the cause of a misoperation, the focus then shifts to formulating a specific corrective action plan (CAP) to mitigate and prevent the misoperation from occurring again. The CAP is formulated in a group setting that includes all PCE regional technical engineers in attempt to develop a well thought out and comprehensive CAP.

After a CAP has been developed for the misoperation, the focus then shifts to the implementation of the specific CAP. AEP has set an internal goal of implementing the CAP within two weeks from the time the CAP was first finalized. This timeframe is aggressive but is in line with our goal of zero misoperations. The short timeframe is in place to help prevent repeat misoperations. One method AEP utilizes to meet this timeframe is our "Express Settings" issue procedure. This procedure allows a qualified engineer to remotely connect to a relay through the AEP network and make remote setting and/or logic changes. This method helps reduce the time that it takes to get settings fixed on relays that are associated with a misoperation. It is a more direct method and bypasses the need for someone to drive out to the station and apply the settings locally.

Occasionally, there will be a need to get an updated short circuit model to implement a CAP. There is a lot of data and different departments that are required to get an updated short circuit model. This has often caused problems in meeting our two week CAP implementation goal. In attempt to improve on this bottleneck, a box can be checked during a model request indicating that the model is needed to mitigate a misoperation and therefore it should be given priority over any other model development work.

IV. CAP Applicability

In parallel with implementing the CAP, PCE is also assessing if the CAP could be applicable to other protection system assets. PCE studies the root cause and tries to determine if the incident is an isolated event (one-off) or if there is reason to believe that the same cause could result in a misoperation to another protection system (ex: error with a standard setting template file that may have been used for multiple relay assets). If the misoperation cause is determined to be an isolated event (one-off) then PCE doesn't do anything extra besides implementing the CAP. However, if the misoperation cause is determined to have applicability to other protection systems, then PCE develops a list of protection system assets that could be affected. A global CAP project is kicked off to mitigate all of the applicable protection system assets. Often these projects can include many protection system assets and take a lot of time to complete. PCE does not currently have any hard timeframe for completing these global CAP projects. They are often blended in with ongoing capital investment work. The main take away is that these global CAP projects are a proactive approach to minimizing similar future misoperations. The execution of these global CAP projects often entails a delicate balance between risk of potential misoperation vs resources needed to mitigate the risk. The "Express Settings" issue procedure is a tool that we can use to help execute on large global CAP projects as long as the CAP is relatively straightforward and does not require site specific engineering analysis.

V. Short Circuit Modelling

A good short circuit model is the foundation for developing reliable protection settings. Over the last few years, AEP has formalized how power elements such as lines and transformers are modelled. AEP has a dedicated short circuit modelling group that focuses solely on modelling and ensuring high integrity of the short circuit base case model. The modelling team has a consistent process for how they obtain data that essentially results in impedance calculations. This could be data from transmission lines and how the lines are physically built all the way to transformer vendor test reports. At the end of the modelling process a peer review of the modelling data is routinely performed before it is handed off to PCE. As part of our settings development process, anytime protection settings are being modified, the protection settings engineer must submit a request for model verification of the power element that they are modifying settings for. This process helps bring to surface any existing incorrect modelling data. We have occasionally found existing modelling data such as line impedances to be incorrect or off by more than 5% which then can start to affect the performance of protection settings. By requesting model verification of any power element that is having its protective settings modified, PCE is hoping to proactively find modelling errors that could result in incorrect protection settings rather than discovering the model and settings are incorrect retroactively due to a misoperation occurring (ex: Zone 1 element overreaching past remote bus due to incorrect line impedance data).

VI. Formalized Peer Reviews

After reviewing many years of misoperation data, AEP has noticed a trend of human error as a root cause to many settings related misoperations. Humans will always make errors and it is almost impossible to fully prevent that, but in attempt to add extra layers of prevention, AEP has instituted a formal peer review process for all protection setting development. In the past, peer reviews were done, but there was a lot of discretion on how the review was completed. PCE has now integrated into our settings issue workflow a formal peer review that contains key aspects that need to be verified. We also have a formal process document that details how the peer reviews should be conducted. Peer reviews that involved BES settings cannot be peer reviewed by just anyone, but instead they need peer reviewed by a qualified engineer (regional, principal, or staff engineer). Anything that is non-BES can be peer reviewed by any competent peer engineer. In past years, the feedback from reviewers and the documentation of the review was not always consistently captured and stored. The current peer review process fixes this by consistently capturing the reviewer's feedback and documenting who the review was performed by. This helps AEP comply with PRC-027 (by showing evidence of a review) and provide better troubleshooting since all review feedback can be retrieved along with who reviewed the settings if any questions may arise in the future. By formalizing peer reviews for protection settings, PCE has been able to issue higher quality settings and catch setting errors before they get applied to the protective relays in the field.

Item	Task	Enter Value	Executed	Executed Time	User
1-	**PCE Peer Review**				
1.1.	Select the type of settings that are being peer reviewed	Line Settings	☑	9/27/2022	s233645
2-	**Aspen Model**				
2.1.	Aspen Model was reviewed and updated as per TEPD-2450	Yes	☑	9/27/2022	s233645
2.2.	*Comments*				
2.3.	Relay devices and coordination pairs are modelled correctly.	Yes	☑	9/27/2022	s233645
2.4.	*Comments*				
2.5.	Proposed settings coordinate with relay devices in the area.	Yes	☑	9/27/2022	s233645
2.6.	*Comments*				
3-	**Calculations**				
3.1.	All calculations required for this asset are accurate and complete	Yes	☑	9/27/2022	s233645
3.2.	*Calculation Comments*				
4-	**TOps Sheet**				
4.1.	*Settings match the RSRF*				
4.2.	*Comments*				
5-	**Settings Templates**				
5.1.	Correct relay settings template was used and populated accurately	Yes	☑	9/27/2022	s233645
5.2.	*Comments*				
5.3.	Relay settings file addresses legacy issues detailed in the robust checklist	Yes	☑	9/27/2022	s233645
5.4.	*Comments*				
6-	**RPA**				
6.1.	*Data points match with RPA file*				
6.2.	*RPA comments*				
7-	**Comments/Attachments**				
7.1.	Attachment any other documents that are required	Import...	☑	9/27/2022	s233645
7.2.	Settings are approved and are good to be issued for implementation	Yes	☑	9/27/2022	s233645
7.3.	*Please enter the comments on why the settings were not approved*				

Figure 1: Formal PCE Settings Peer Review Checklist

As an even further improvement to our formal peer review process, PCE has created a Line Settings Robust Checklist. This checklist includes items that may often get overlooked and items that past experiences have deemed need extra attention from the setter and also the peer reviewer. The Line Settings Robust Checklist provides detailed content on what a setter and peer reviewer should be focusing on. All aspects of line relay settings development are considered in this checklist (short circuit modelling, calculations, relay setting files, compliance documentation). This checklist is especially important and useful when working with older existing relay settings. The Line Settings Robust Checklist is a one-stop shop document that contains all the special critical settings that need to be considered and given special attention when performing line settings.

VII. Automated Relay Settings

To further reduce human error and promote consistency in development of protection settings, PCE has worked with an outside consultant to development an Automated Relay Settings (ARS) tool. ARS has many different benefits, but the three most important are its ability to reduce human error, its ability to reduce engineering labor time/cost, and its ability to enforce consistent setting criteria/philosophies.

The way ARS works, is that a user enters high level information into a user interface (UI) dashboard that ties the ARS setting tool to the short circuit simulation tool. The user also enters in high level information about the protection scheme they are setting such as scheme type (DCB, Current Differential, Step Distance), CT ratio, PT ratio, desired maximum load MVA, and line voltage. The tool then will automatically interface with the short circuit simulation tool and take all the necessary faults and run the faults through PCE defined setting criteria/philosophies to then result in proposed protection settings. The user will then quickly review and perform sanity checks on the auto generated settings before endorsing them as final settings. The user can deviate or change the auto calculated settings if there is a good valid reason for doing so (any deviation must be documented).

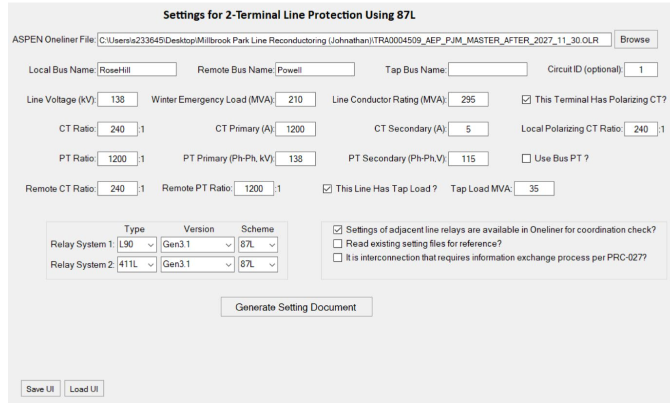

Figure 2: ARS User Interface

Once the user has final settings, ARS can then push all of the settings into the appropriate relay setting file templates. This aspect is a huge time saver and very important towards reducing human error. ARS is initially mapped to synch up with PCE standard setting file templates so all settings are consistently populated in files that will eventually be issued to the field to apply to the relays. This approach is like an assembly line concept, where a lot of upfront effort is put into synching the ARS calculated settings to the correct spot in the AEP standard setting file template so that after the initial effort, setters will then gain extreme efficiencies by not having to manually populate anything in the setting files.

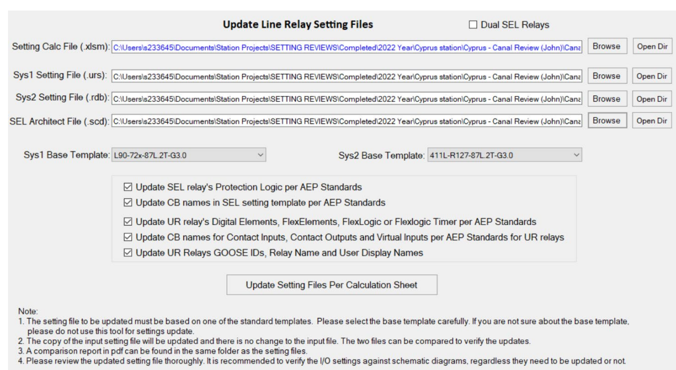

Figure 3: ARS Auto Settings Populate User Interface

ARS can be used for transmission lines/buses, breaker control/failure, distribution transformers/buses, transmission transformers, and transmission capacitor banks. One of the key benefits of having a central settings development tool like ARS is that whenever a setting calculation or philosophy changes, the tool can be quickly updated and any new settings developed will be set utilizing the new changes. This is a vast improvement vs older methods where all setters had to hear about any new setting calculation/philosophy changes and then they had to remember to utilize these new changes the next time they developed settings. ARS now does this all for the setter behind the scenes without any thought very similar to a software update on your iPhone.

VIII. PRC-027 Area Coordination Reviews

PRC-027 is a very new North American Electric Reliability Corporation (NERC) standard that PCE must comply with. One of the standard's requirements calls for performing a periodic relay system coordination review every six-calendar years. PCE has already started performing this protection system coordination review and anytime a line terminal is flagged as not coordinating during the review, then PCE will do a complete reset of the line terminal and get it up to speed with our latest setting criteria/philosophies. This takes a considerable amount of time, but since PCE will already be making some setting changes to the terminal to comply with PRC-027 it has been deemed worthwhile to just go ahead and modernize all the line settings for the line terminal. This allows us to not only comply to PRC-027 requirements, but it also helps us proactively fix legacy setting issues and implement modern enhancements all in attempt to prevent future misoperation risk. So far AEP has reset and modernized the settings for all of our 500-765kV line terminals. The next phase of setting resets and modernization has begun on the 200-345kV line terminals and that phase should complete around the end of 2022. AEP will continue to work our way down to lower voltage levels until all BES line terminals have had their settings reset and modernized to our latest settings criteria/philosophies.

IX. Relay Failures

Besides human error related incorrect settings as a trending misoperation cause, AEP has seen a trend in relay failures causing misoperations. Typically, you would expect older electromechanical relays to have higher failure rates, but as of recent we have been experiencing high failure rates with microprocessor relays. We have experienced numerous misoperations in many different General Electric (GE) microprocessor relays. Most of these misoperations have been caused by a memory corruption also referred to as a "bit flip" which results in the relay asserting protection elements during non-fault conditions. PCE has worked with GE on solutions to mitigate this "bit flip" issue in attempt to prevent future misoperations. GE has since fixed this issue in newer firmware releases which allow the relay to first detect if a "bit flip" scenario is present before allowing a protection trip to be asserted. In response to this, AEP has rolled out a large firmware upgrade initiative for all of our applicable GE relay assets so that they can be upgraded to a firmware version that will prevent nuisance "bit flip" misoperations. This firmware upgrade initiative will span a few years and take a lot of effort to complete, but based on the number of "bit flip" misoperations that we have experienced the effort is justified. By upgrading the firmware, other minor enhancements will also be realized as well which should incrementally increase reliability.

A few other initiatives that AEP has been working through are our GE Upgrade and Schweitzer Engineering Laboratories (SEL) Upgrade programs. These programs aim at proactively upgrading GE and SEL relays that are very old and have limited vendor support. During these upgrade programs, the existing relay hardware is swapped out with a similar relay, but that relay will have all new hardware therefore breathing new life into the relay for many more years to come.

AEP still has a decent amount of electromechanical (EM) relays that are very old. During capital investment projects, a lot of priority is given to proactively upgrade these older EM relays with newer microprocessor relays. From time to time, we have observed failures in our EM relay fleet and although these failures haven't caused a significant trend in regards to misoperations, AEP acknowledges the need to proactively upgrade these electromechanical relays due to lack of oscillography, old age, difficulty in maintaining, and limited flexibility.

X. Relay Setting Criteria / Philosophy Improvements

AEP's PCE department has a rich history in having detailed relay setting criteria and guidance. However, after misoperations PCE has embraced change and has pivoted from being very dependable to being more secure. As misoperation trends develop PCE has changed some of our setting guidance. Some examples of these changes will be highlighted below.

For many years PCE has set instantaneous overcurrent elements. We have experienced misoperation trends with these elements and have acknowledged the difficulty in ensuring good reliable coordination with them. This has led us to a philosophy change in regard to instantaneous overcurrent elements. If zone 1 distance elements are enabled and set per our criteria, then we will no longer set instantaneous overcurrent elements. The main concept behind this is that a distance relay will have a fixed reach making it more secure while an instantaneous overcurrent element can have its reach dynamically change based on the system configuration and available fault current thus making it more prone to overreach misoperations.

High speed Power Line Carrier (PLC) based schemes like Directional Comparison Blocking (DCB) and Permissive Overreaching Transfer Trip (POTT) are very reliant on a correct directional assessment in order to work correctly and not misoperate. Over the past few years, PCE has enhanced its directional setting guidance for carrier-based schemes. Some of these improvements include utilizing negative sequence polarizing when mutual coupling is present, using the same exact directional method at all terminals of a line, and forcing the relay to only use one directional method so that it doesn't have the ability to pick among multiple directional methods. PCE has also increased the standard carrier coordination time delay to 24 milliseconds in all cases to provide more time to receive a block. Setting guidance has been updated to desensitize carrier forward ground overcurrent elements so that the schemes aren't being tested as much. The guidance is to try to set at 600 Amps primary and only reduce if you have sensitivity issues. This will help to prevent the carrier scheme from being overly sensitive. The last major carrier based scheme improvement that PCE has made recently is in regards to delaying our carrier forward ground overcurrent element by 8 cycles so that the carrier forward ground distance element can act first since the distance elements are more secure.

Current differential schemes have been very reliable for AEP, but in recent years we have experienced some issues that have caused PCE to change our setting guidance and desensitize our current differential pickups. Originally, the current differential pickups were set very sensitive (often at 1 or 2 Amps secondary), but now our guidance starts with a current differential setting of 5 Amps secondary and only goes lower if the setter runs into sensitivity issues. By desensitizing the current differential elements, it helps to ride through possible Current Transformer (CT) saturation, especially in the event when a terminal has two line breakers and the CTs are summed external of the relay and there is a close by external fault.

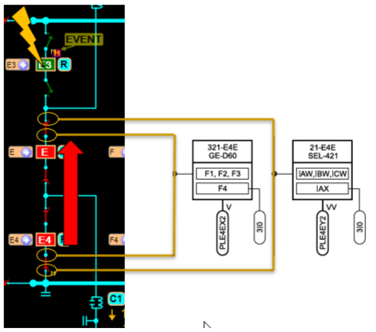

Figure 4: CTs Summed External of the Relay

AEP has had a lot of misoperations with our ungrounded wye transmission capacitor bank protection scheme. These capacitor banks are protected by a neutral shift or compensated voltage differential element. We have had numerous incidents where a capacitor bank misoperated due to system voltage imbalance. We have tried a lot of different methods to improve the security of these capacitor bank protection schemes, but have not been very successful at mitigating the risks with these neutral shift / compensated voltage differential schemes. So AEP has decided to start aggressively transitioning away from the ungrounded wye capacitor bank design and start installing grounded wye capacitor banks that have embedded CTs within various spots on the capacitor bank. The CT measurements provide a much more reliable and secure way to protect the capacitor banks vs the voltage based neutral shift / compensated voltage differential. It will take many years to complete this capacitor bank design transition, but regardless AEP has started the transition with upgrade priority given to any capacitor bank that has previously misoperated.

XI. CT Saturation

CT saturation has been a big trending cause for misoperations within the last few years for AEP. It has been discovered that our method for selecting connected CT ratios has not been very consistent and has not put enough focus on potential CT saturation. Most of our CT saturation issues have resulted from protection systems that interface with multiple CTs that are summed externally before connecting to a relay. The CTs aren't always performing in a similar fashion and when this happens it creates operate current to the relay. There are a lot of factors that can cause the CTs to not perform in a similar fashion when they are summed externally before connecting to a relay, but the biggest reason why is due to a lower than adequate connected CT ratio. To combat this issue, PCE has developed a formal CT saturation calculation spreadsheet to help engineers determine if a CT is sized optimally to prevent CT saturation. This spreadsheet allows an engineer to enter site specific data and determine an appropriate CT ratio for their protection system that they are working on. PCE has also added design guidance to use the highest available existing CT ratio and only lower the CT ratio if sensitivity issues arise. In some cases, using the max available CT ratio would still result in potential CT saturation. This is the case if the breaker was not ordered with high enough CTs from the factory. It is hard to fix this after the breaker has been ordered and shipped to the station. In order to prevent this situation of ordering a breaker that doesn't have a high enough max CT ratio, PCE has developed a scoping CT saturation checking spreadsheet. This tool will allow a scoping engineer to accurately estimate what would be the most idea breaker CTs to order for any new breaker with very basic input data such as available bus fault current and the X/R ratio. With these improvements, PCE is optimistic that our CT saturation misoperation trend will go away.

XII. Misoperaton Metrics

PCE and TFS P&C have collaborated to create a real time misoperation metrics dashboard within Microsoft's Power BI data visualization software. This dashboard allows for visual display of our misoperation rate for the current year and also past years for a misoperation trend comparison.

There is also a detailed dashboard page that zooms into relay settings related misoperations and categorizes them into the North American Transmission Forum (NATF) subcases. The dashboard metrics contain even more categories such as the AEP region that the misoperation occurred in, the type of protection element that misoperated (ex: DCB, Line Differential, Instantaneous Overcurrent, Distance Zone, etc…), power element type (ex: Line, Transformer, Bus, Capacitor Bank, Reactor, etc…), and whether it was a settings issue or a print design issue. All of this data can help us identify trends and better tailor regional training, improve standards designs, improve settings guidance, and add preventive process controls.

Figure 5: PCE Metrics Dashboard

XIII. Conclusion

AEP has observed a lot of good meaningful misoperation data throughout the last four years when we really started to document and index our misoperation data. This data has allowed AEP to make the necessary changes and implement new tools all in line with continuous improvement towards our goal of zero misoperations. Within the last four years, AEP's misoperation rate has steadily been decreasing. A lot of the improvements mentioned in this paper are heavy contributors to why our overall misoperation rate continues to decline. With continuous improvements and building on the reduction momentum that AEP is already seeing, it is our goal one day to acheive zero misoperations.

XIV. BIOGRAPHY

Ross D. Stienecker is a Principal Regional Engineer at American Electric Power (AEP). He graduated from Ohio Northern University with a BSEE. Ross is a registered Professional Engineer (PE) in the state of Ohio. He has worked at AEP for 11 years in the Protection and Control Engineering (PCE) department primarily supporting the Ohio region. His areas of expertise include relay settings development with focus on line relay settings, relay settings review, project scoping, NERC compliance, print design work, and system protection misoperation analysis.

Manish Thakur is Director of Protection and Control Engineering at American Electrical Power (AEP) with 26 years of experience in Protection and Control (P&C). His current responsibilities at AEP include system protection and control, compliance and relay misoperation investigations of transmission systems up to 765kV. His areas of expertise include HiZ fault detection, series compensation application on EHV systems, transient and real time simulations, Standardization, and Digital Substation. Prior to joining AEP, Manish worked with ABB and General Electric as a P&C application and consulting engineer. Manish received his Bachelor of Science in India and Master of Science from University of Manitoba, Canada. Manish is a member of IEEE and is a Professional Engineer (PE) registered in Ohio.