# Challenges in Analyzing Single Points of Failure Based Tripping Sequence and Fault Clearing Time for TPL-001-5.1 Compliance

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***Abstract*—Transmission planning teams have relied on protection engineering teams for Protection System performance data for the steady-state and transient stability studies performed as part of NERC TPL-001-4 standard compliance. With the upcoming NERC TPL-001-5.1 revision (effective July 1, 2023), the study requirements for determining the impact of non-redundant Protection Systems have been expanded. This has resulted in a more detailed Protection System performance analysis to generate the data required for the planning studies. This paper discusses the challenges related to this new requirement and strategies to tackle these challenges based on the practical knowledge gathered by the authors from related projects.**

***Keywords—NERC TPL-001, Non-redundant, Protection, Planning, Delayed Fault Clearing***

## I. Introduction

The existing 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 outages. Transmission planners must perform steady-state and transient stability studies based on the standard's contingencies and event requirements, which are divided into seven categories (P1–P7) [1].

Category P5 of the standard, which is the focus of this paper, requires both steady-state and stability studies of events that have a delayed fault clearing time due to the failure of a non-redundant relay protecting the faulted equipment to comply with the TPL-001-4 standard. In the upcoming TPL-001-5.1 revision, the P5 category is expanded from failures of non-redundant relays to failures of non-redundant components of a Protection System. As per the latest revision, the following can be considered a non-redundant component of a Protection System [1]:

- A single protective relay that responds to electrical quantities without an alternative (which may or may not respond to electrical quantities) that provides comparable Normal Clearing times [1: Footnote 13a]
- A single communications system associated with protective functions necessary for the correct operation of a communication-aided protection scheme required for Normal Clearing (an exception is a single communications system that is both monitored and reported at a Control Center) [1: Footnote 13b]
- A single-station DC Supply associated with protective functions required for Normal Clearing (an exception is a single-station DC Supply that is both monitored and reported at a Control Center for both low voltage and open circuit) [1: Footnote 13c]
- A single control circuit (including auxiliary relays and lockout relays) associated with protective functions, from the DC Supply through and including the trip coil(s) of the circuit breakers or other interrupting devices, is required for Normal Clearing (the trip coil may be excluded if it is both monitored and reported at a Control Center) [1: Footnote 13d]

The newly expanded definition of the P5 category contingencies poses several challenges that require significantly more effort in defining the contingency scenarios for planning studies. These challenges are:

- Identifying Protection Systems with non-redundant components or single points of failure (SPOF) across the entire BES system
- Determining the delayed fault clearing times accurately, which has become increasingly difficult to estimate due to the increased complexity of the Protection Systems, especially for ground faults
- Creating corresponding outage files for steady-state and transient stability studies (outage files are specifically formatted automation scripts that contain instructions for simulating contingency scenarios in given planning software)

The following sections provide an overview of the SPOF analysis approach, describe the challenges related to the expansion of the P5 category and SPOF analysis, and discuss practical solutions to tackle the challenges.

## II. Integrated Analysis Approach

Power system stability analysis (transient and steady-state) and protection analysis are performed using separate specialized analysis tools. This separation resulted from the traditional analysis paradigms that required minimal interaction between them and the general drive for optimization. The TPL-001 SPOF analysis requires integration between these simulation tools. Therefore, to understand the integration approach, it is important to understand the differences between the planning and protection analysis tools.

### A. Planning and Protection Simulation Tools

The software tools used in planning studies are capable of modeling slow transients (around 0.5–10 Hertz) in power systems. These tools model the network components (lines, transformers, shunts, etc.) in the phasor domain as a static model. Therefore, the very fast electromagnetic transients are ignored. The slow power system transients of generators, synchronous condensers, and field voltage control systems are modeled with dynamic equations in the time domain. The dynamic equations are linked to the phasor domain equations using current injection models and in return the produced voltages are fed back to the dynamic model in a calculation loop. This simultaneous calculation method is an efficient model that is sufficient for modeling power system dynamics and performing stability analysis for traditional power systems.

When planning studies need to consider the impact of power system contingencies, such as short-circuited network equipment (faults) and outage of network equipment, they also need to include the response of the Protection System. Typically, the Protection System operates very fast, within a few cycles, and can be assumed to be within a pre-defined set of operation times. However, when the response of a Protection System has been compromised due to the failure of a non-redundant component, such as the ones defined for the P5 category, the Protection System performance cannot be generalized, and a more detailed analysis is required.

The software tools for protection analysis are designed to model Protection Systems as a layer on top of the network model. The model needs to represent zero-sequence components of voltages and currents accurately and have enough details of protective relays to represent a good approximation of relay operation system conditions. The protection analysis software tools typically utilize simplified protective device models that ignore all the transients of voltages and currents and evaluate the protective device operation based on steady-state values. The tools can also perform stepped-events analysis (SEA), which involves recalculating the fault currents and voltages at each network change resulting from a sequential protection operation and then re-evaluating other protective devices that can detect the fault until all protective devices have dropped out.

### B. Integration Approach

North American utilities use power systems simulation tools that specialize in modeling and simulating transients or Protection Systems. Commercial tools are available for modulating the two types of simulation platforms and allow co-simulations [2], [3]. Co-simulation requires both simulation tools to support importing variables from an external source in small time steps and potentially an iterative solution to enhance the stability of the simulation results, which is not supported by all the simulation tools currently available. The simplified concept is shown in Fig. 1. This approach requires a complete alignment of the protection and planning network models. This is often not practical due to significant differences in the modeling conventions between protection and planning models. There are initiatives to consolidate power system models in one source that could facilitate co-simulation studies [4], [5].

There is a second approach based on feeding protection model simulation results to the dynamic model of the system, as shown in Fig. 2. It compensates for the deficiency of planning tools in modeling SPOFs by taking advantage of detailed protection modeling capabilities of protection tools. The two systems are modeled separately in their respective tools. The operation of the same system components is translated from Protection System to planning system and finally fed forward for stability simulation.

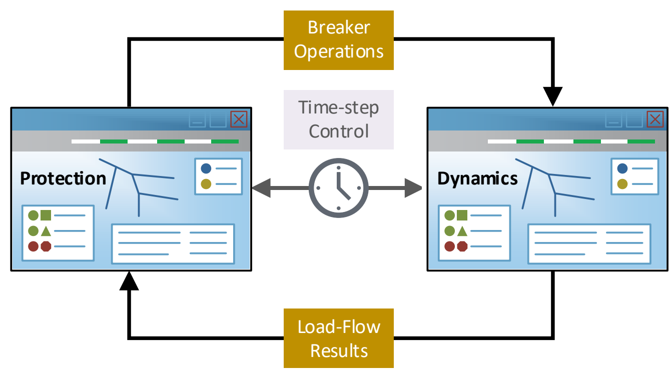


Fig. 1. Co-simulation of protection and planning systems.

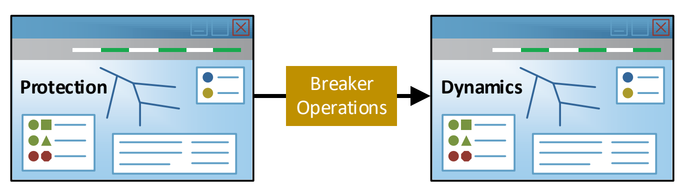


Fig. 2. Open-loop simulation of protection and planning systems.

The second approach was selected over the co-simulation approach due to its flexibility. Compared to the co-simulation approach, this is a feed-forward approach, which has the drawback of ignoring the transients of voltages and currents during Protection System simulation. However, this approach works with all available software tools with or without automation capabilities. This approach also does not require complete alignment between the two models and instead relies on an external mapping table for converting results from protection to dynamic model.

## III. Challenges Related to Expansion of P5 Category and TPL-001 SPOF Analysis

### *A. SPOF Identification*

SPOFs of concern are determined by cases where the Protection System is expected to have a delayed fault clearing time due to the failure of a non-redundant component of the Protection System. Identifying and recording SPOFs can be tedious and pose a significant challenge for a utility. Common types of SPOFs are discussed below in detail for each component of concern under TPL-001-5.1.

#### *1) Protective Devices*

A protective relay is considered a SPOF if there were no alternative relays that would provide comparable fault clearing times. Where evidence exists to show that two or more identical relays are configured the same, fault clearing times can be considered the same. It becomes more challenging to provide evidence of comparable fault clearing times when the alternative relays are different, considering such things as version, model, manufacturer, configuration, operating principle, location, etc. A larger number of alternative relays within a protection group can further complicate this SPOF identification, such as in electromechanical protection schemes. The typical areas of concern are non-redundant bus differential schemes, and electromechanical schemes without full redundancy. Additionally, there is no exception allowed for monitoring and reporting of protective device operation that will result in the assessment of larger number of SPOFs.

#### *2) Communication Systems*

Communication systems typically contain many components that could be shared between protection schemes, such as input and output cards, multiplexers, signal converters, transmitters, receivers, etc. Even if all other components of the communication systems are redundant, the communication medium itself might be shared and susceptible to failures. For example, consider if dual microwave systems could be relied on during a severe storm that encompasses both antennas. Or consider high-performance large-scale communication networks—such as those using multiprotocol label switching (MPLS) or 5G—which tend to have built-in redundancy but with a very small probability of a loss or delay to service. SPOF identification of communications systems can be complicated, requiring a full redundancy assessment of the many communication system components and, in some cases, an assessment of the overall dependability of the communication network itself. Typical areas of concerns will be around older communication aided tripping schemes, which have higher likelihood of being non-redundant.

#### *3) DC Supply*

Station DC Supply is typically required by multiple components that make up the protection trip path, including the protection relays, auxiliary relays, breaker trip coil, and associated wiring. NERC's Technical Rationale For TPL-001-05 [6] explains which DC Supply circuit elements need to be considered when determining the DC Supply SPOF and the DC Control Circuitry SPOF. The DC Supply elements stop at the DC panel or the first DC protective device, such as a fuse or main breaker. The DC Supply could be a SPOF, if any of the DC Supply components are shared among the other interfaced Protection System components. Since a DC Supply failure can simultaneously disable many Protection Systems, it can be complicated to provide evidence of comparable fault clearing times under this contingency. Typically, older BES stations are expected to have non-redundant DC Supplies.

Depending upon the complexity of the protection system design, a more thorough review of the DC path from the supply to the trip coil and from the supply to any protection components (such as relays) needs to be conducted to identify a DC Supply related SPOF. A notable example was one assessment where Protection Relay A was powered by DC Supply A and tripped Trip Coil A, which was powered by DC Supply B. Similarly, Protection Relay B was powered by DC Supply B, and tripped Trip Coil B, which was powered by DC Supply A. A high-level review could have overlooked this as a SPOF in the DC Supply for this Protection System since the relays, and trip coils each individually have redundant supplies. However, a failure in either supply would disable the entire Protection System in this case. This example highlights the need for a detailed simultaneous assessment of all the systems on a DC Supply.

#### *4) Control Circuitry*

As per NERC's Technical Rationale For TPL-001-05 [6], control circuitry includes everything from where the station DC supply terminates to all the way to the trip coil. Panel wiring, auxiliary and lockout relays, and supply circuits feeding the protective relays are considered under the control circuitry category. The SPOF identification process is very similar to that for the DC Supply but focuses on the components' failures, including auxiliary relays, lockout relays, trip coils, and associated wiring. An example of a key difference would be a single lockout relay initiated by redundant protection relays powered by separate DC supplies and that trips redundant trip coils through separate DC supplies. In this example, SPOF assessment of the DC Supply alone would not identify any issues. The additional control circuitry path must also be assessed to identify the lockout relay as a SPOF. DC Supply and control circuitry SPOF identification together requires an extensive review of the critical protection trip paths in the protection circuit designs. It shall be noted that the failure of an entire DC panel is generally considered a control circuitry SPOF.

Many utilities still have legacy circuit breakers with a single trip coil that represent SPOFs. Although trip coils are allowed an exception if they are monitored and reported, but the same exception is not allowed for the trip wire from the control house to the circuit breaker rendering the exception impractical.

*5) Other SPOF Identification Challenges*

SPOF information for TPL-001-5.1 is not traditionally readily available and typically requires a detailed review of anticipated protection relay fault response, communication system configurations, and Protection System circuitry. A broad expertise level across these areas is needed for these assessments, likely involving teamwork between experts in protection relays, communication systems, and protection circuit design. System planners also need to be involved in helping define acceptable margins for Normal Clearing times. For example, two different relay models performing the same function will likely still have very slightly different maximum operating times. Still, planners may agree that less than one cycle of additional delay could be acceptable if the faster relay is out of service to ease the burden of the SPOF identification. This cross-functional team may need to review relay specifications, test relays, carry out protection simulations, define and test communication system performance requirements, and review system configuration and designs, including the review of Single Line Diagrams (SLDs), DC schematics, and other drawings.

SPOF identification can require a large team effort, and since TPL-001-5.1 studies need to be completed periodically, the results from the SPOF identification should be recorded for future use. Managing and maintaining the information as systems change is critical to avoid another large-scale SPOF identification effort for the next round of studies. This requires creating a system to manage SPOF information, so it is readily available for TPL-001-5.1 studies. Processes must also be implemented to ensure that the SPOF information is updated when impacted by system changes. These efforts typically will require coordination across different departments within a utility, and they need to be managed indefinitely into the future as team members change.

*B. Tripping Sequences and Fault Clearing Time Calculation*

As discussed earlier, the P5 category requires the application of a single-line-to-ground (SLG) fault on equipment combined with the failure of a non-redundant component of the Protection System protecting the faulted equipment. The standard requires the study of network equipment that is connected to the EHV and HV system and is of the following types [1]:

- Transmission circuits
- Transformers
- Bus sections
- Generators
- Shunt devices

Each equipment type presents unique challenges in determining the worst-case delayed fault clearing time due to the variations in the Protection System design, possible fault locations, and response from backup Protection Systems. The transmission planning teams may incorrectly use three-phase to-ground (TPH) fault clearing times for SLG faults for major contingencies, such as DC supply failure or bus differential protection failure, without recognizing the potential drastic difference in Protection System response for the two different fault types.

As the complexity of the Protection Systems has grown, it has also become increasingly difficult to accurately predict the Protection System tripping sequence for a given contingency scenario without simulating the Protection System's behavior. The need for protection simulations poses specific challenges related to protection modeling, as discussed below.

*1) Short Circuit Model Detail*

The use of a protection simulation platform for analyzing Protection System behavior can be limited by the detail of the network model and the protection model being utilized.

Typically, short circuit models developed by protection engineering teams utilize a bus-branch model that models a single bus for each nominal voltage within a substation. The bus-branch models are employed due to the lower model maintenance effort and ability to support the commonly performed protection studies with sufficient detail. However, the impact of detailed substation configuration on the tripping sequence and fault clearance during contingencies cannot be analyzed accurately [7].

Alternatively, the node-breaker model represents the station configuration more accurately. Still, it can present more challenges in model maintenance, such as greater effort in building the model and the need for specific software platforms to help create and maintain the detailed node-breaker model [7].

TABLE I. PROTECTION MODELING DETAIL LEVELS

| Level | Protection Modeling Detail | Analysis Supported |
|---|---|---|
| 1 | Includes distance, overcurrent, fuses, reclosers, and over/ under voltage protective elements, which are typically modeled for lines, transformers, and generators | Utilized for protection settings, design and evaluation, and basic protection coordination review |
| 2 | Includes communication-based protection, such as differential protection, teleprotection schemes, and simple transfer trips | Utilized for enhanced protection coordination review, tripping sequence, and fault clearing time analysis |
| 3 | Includes bus differential, breaker failure protection, and complex transfer trip schemes and typically requires a node-breaker network model | Utilized for detailed protection coordination review, tripping sequence, and fault clearing time analysis for complex contingency scenarios, such as a stuck breaker, bus section faults, etc. |

Additionally, the protection modeling detail varies across the industry, which can be categorized into three levels, as shown in TABLE I. .

The level of protection modeling detail adopted by a utility depends on the analysis it plans to use the model for. Most utilities go up to Level 2 to take advantage of the sequence of events simulation capabilities of modern protection simulation platforms, especially to streamline NERC PRC-027 R2 compliance [8].

Since it is uncommon to have protection modeling detail up to the Level 3 category, some SPOFs cannot be assessed through simulations alone and require manual input. For example, in the absence of a node-breaker model and breaker failure protection, we cannot simulate control circuitry or trip coil failure if the tripping sequence needs to consider the breaker failure protection operation.

Note that the protection studies for TPL-001-5.1 are run with SPOF contingencies applied (i.e., with Protection Systems being taken out of service). Therefore, engineers need to evaluate if they need to model a certain type of protection in the model to perform the analysis. For example, in the case of performing a protection study for a bus that has single bus-differential protection, the engineer does not need to model the bus differential protection, as the protection study will be conducted with the single bus-differential protection out of service. Furthermore, the SPOF study is no longer required if the bus has a redundant Protection System. Therefore, knowing the type and frequency of SPOFs in the system becomes important when determining the level of modeling detail required.

#### 2) *Model Maintenance Effort*

It is critical to have an up-to-date and accurate system-wide network and protection model to utilize protection simulations. Therefore, the utilities need to establish a process to maintain the network model and the protection model continuously. Although having greater detail in the model may seem desirable due to the potential of reducing manual effort in the protection analysis, it can substantially increase the model maintenance burden. Therefore, it is important to consider the trade-off between modeling effort and benefit on a case-by-case basis.

### *C. Feeding Protection Results Into Planning Studies*

Upon completing the tripping sequence and fault clearing time analysis in the protection simulation platform, the operations of breakers will need to be translated to the corresponding outages of planning model components. This process is called contingency conversion and requires accurate and comprehensive mapping of network components between the protection and planning models.

Different simulation tools define breaker operations differently. In protection tools operation of breakers at the end of the lines or bus-ties between two buses can be modeled. Newer versions of planning tools are capable of modeling more details. Still, provisions are often made to convert breaker operation to the outage of entire lines or line sections in the planning model.

Another complication in the contingency conversion process is the different details of the models used in protection and planning tools. Most differences can be categorized into the following:

- There may be buses that do not have an equivalent in the other model, as shown in Fig. 3. These buses are added for modeling taps, mutuals, or other details that do not affect power system simulation but have other significance for the network under study.
- The protection models sometimes include further detailed bus structures such as ring or breaker and half, while the planning models use simplified bus structures which do not include breaker structures. A breaker-and-half bus structure is shown on the left side of Fig. 4, while the right side shows a simple bus structure.

There might be one-to-one, many-to-one, or one-to-many matches between the buses of protection and planning models. Also, there might be tapping buses in one of the cases that have not been modeled in the other. Therefore, it would be complicated to develop a methodology that can convert the operation of breakers from protection models to planning models.

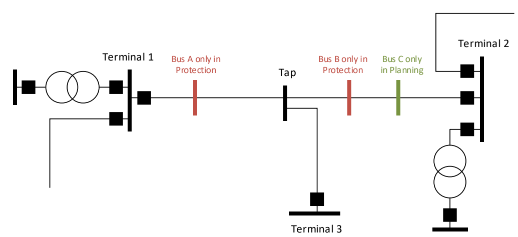


Fig. 3. Differences in number of buses in protection and planning models.

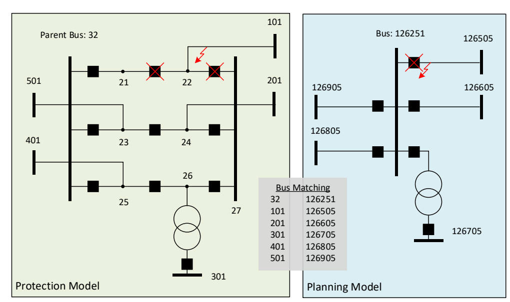


Fig. 4. Comparison of a breaker-and-half bus configuration representations in protection and planning models.

## IV. Approach to Tackling Challenges

### *A. Strategy on Collecting and Managing SPOF Data*

Before collecting SPOF data, it is important to define what is considered "comparable Normal Clearing times." For example, if two different protection relay models use similar operating principles and settings, one approach could be to assess the operating speed of each relay fully. Another approach could be to use a conservative estimate for the difference in relay operation time and add that as a margin to the Normal Clearing time. The latter approach can reduce the scope of what is considered a SPOF without the need for fully testing each minor difference in Protection Systems. The former approach provides a more granular assessment that may be less prone to errors (simply adding a margin to the Normal Clearing time does not consider changes to tripping sequences that may occur under longer fault clearing times). The former approach can also reduce the number of planning violations initially flagged since maximum fault clearing times do not need to have as much margin added to cover assumptions.

*1) Protective Devices*

For protection relay SPOF, ideally, a database or short circuit model can be used to identify the relays and associated settings used to protect an element. Unless relay models and versions are identical, test records, manufacturer specifications, or protection standards may need to be reviewed to determine any differences between the relays and maximum tripping times. It is likely not practical to go into this level of detail for each group of relays. Instead, some margin could be added to the Normal Clearing time to account for this (or it may already be included in the Normal Clearing time). Protection settings also need to be compared to check for any differences that could impact relay fault response. Even if relay settings are similar between different relay models, fault response could still differ in some cases. Short circuit protection simulation using detailed relay models can help to test for differences in relay response, reducing the effort needed to compare relays. The use of automated short circuit simulations to assess fault response with each relay out of service, one at a time, is recommended regardless of redundancy. This tests for differences in relay configuration or response, and it does so with a model that has likely already been prepared to carry out the TPL-001-5.1 fault simulations.

*2) Communication Systems*

Some utilities may declare that their normal clearing times are determined when communication aided tripping schemes are disabled. Although, it may eliminate the SPOF consideration for communication systems, but if a mix of long lines and short lines exist in the network, then this method can be problematic due to potential stability problems with slower clearing times.

When the communication aided schemes need to be considered, the SPOF identification can often be simplified by using the exemption rule for a single communications system monitored and reported at a Control Center. This can reduce an otherwise complex assessment to a simple check for monitoring and reporting; however, the evidence will need to be documented. If it is not monitored and reported and there is only a single communication system, then it is also straightforward that a communication outage needs to be simulated. A complicated case arises if there are alternate communication systems that are not monitored. In this case, the systems need to be reviewed for any single point of failure between the relays at each terminal. A good starting point would be to check for the use of different communication mediums. Otherwise, there could likely be a SPOF in the medium itself. From there, drawings need to be reviewed point-to-point for each communication circuit to check for any other SPOF.

Communication system SPOF information should be recorded to identify if the system is monitored, and if not, any components that present a SPOF should also be recorded. It is important to list the components that present the SPOF so they can readily be addressed if needed. This SPOF information should be tracked in a database associated with the impacted Protection Systems in a manner readily available for protection simulations. It is important to note that, while most communication systems only negatively impact the faulted line when out of service, Directional Comparison Blocking (DCB) schemes are an exception that can operate for faults on neighboring elements when the DCB is out of service. In this sense, most communication system SPOF can be associated with the line they protect, except for DCB schemes that must be associated with each neighboring element.

*3) DC Supply*

DC Supply SPOF identification can often be simplified by using the exemption rule for a single station DC Supply monitored and reported at a Control Center for both low voltage and open circuits. This type of monitoring generally requires installation of a stand-alone battery monitoring system. This can reduce an otherwise complex assessment to a simple check for monitoring, excluding this SPOF if monitoring exists. If it is not monitored and there is only a single DC Supply at a substation, then it is also straightforward that a full substation protection outage needs to be simulated. The complicated case arises if there are alternate DC supplies that are not monitored. In this case, the systems need to be reviewed for any single points of failure in the DC supplies that would impact protection response. A good starting point would be to check drawings for the supplies themselves, from the batteries to the distribution panel.

For more complex designs, additional drawings would need to be reviewed for each protection group, checking point-to-point from the distribution panel to the protection relays, trip coils, and any other devices that require DC power within the protection circuit. In performing this assessment, it is important to consider the impact of an outage to either DC Supply on the entire Protection System (for example, checking that Supply A is used entirely for the protection of System A and vice versa, without any interdependencies).

DC Supply SPOF information should be recorded to identify if the system is monitored, and if not, any components that present a SPOF should also be recorded. It is important to list the components that present the SPOF so they can readily be addressed if needed. This SPOF information should be tracked in a database associated with the impacted Protection Systems in a manner readily available for protection simulations. DC Supply SPOF will typically impact multiple protection groups within a substation. This SPOF information needs to track which protection groups are associated with each DC Supply so that the appropriate protection groups can simultaneously be taken out of service during the simulation of each DC Supply outage.

*4) Control Circuitry*

Control circuitry SPOF identification requires a review of drawings for each protection group, checking point-to-point from the protection relays to the trip coil for any single point of failure. If no SPOF exists except that protection relays share a common trip coil, additional SPOF simulation can be avoided by using the exemption rule for a trip coil that may be excluded if it is both monitored and reported at a Control Center. However, in all likelihood the single trip coil utilizes a single trip wire from the control house to the circuit breaker, which does not have the same exception, thereby rendering the exception impractical.

Control circuitry SPOF information should be recorded to identify if there is a SPOF that needs to be considered for simulation. Any components that present a SPOF should be listed to be readily addressed if needed. If the trip coil present a SPOF, the record should also include whether monitoring exists for the trip coil. This SPOF information should be tracked in a database associated with the impacted Protection Systems in a manner readily available for protection simulations. For protection relays that trip multiple breakers (such as bus protection), a trip coil failure would only impact one breaker at a time. To be ready for simulations, each breaker that has a SPOF in the trip circuit should be explicitly listed. Control circuitry SPOF can typically be simulated as a stuck breaker. Still, special consideration must be taken for complex bus designs (i.e., breaker-and-a-half, ring bus, etc.) when the short circuit model is not modeled in this detail. These cases may require updating the short circuit model to a detailed bus-breaker model to simulate the SPOF accurately.

*5) Other SPOF Data Collection Considerations*

Collecting SPOF information is a large undertaking. It is important to have a clear picture of how the information will be used in simulations before starting on this journey to ensure that the information is readily available for simulations. It is also critical to keep this information up to date as systems change to reduce future efforts as periodic studies are repeated. Making this information a required field in master assets management systems such as the protection relay or substation asset database can help to ensure that it is recorded as assets are added to the system or changed. It is also important to have processes and procedures in place to help ensure that these fields are updated. SPOF assessment can be a tedious task, and ultimately investing in Protection Systems to eliminate SPOF can be valuable both to reduce the effort required in TPL-001-5.1 assessments and, more importantly, to make the power system safer and more reliable.

*B. Stepped-Events Analysis Based Protection Simulations*

As discussed earlier, accurate determination of tripping sequence and fault clearing time require protection simulation software due to the increased complexity of the protective devices and the Protection System. While the protection simulation can be performed in several ways, the preferred method for analyzing tripping sequence and fault clearing times is stepped-events analysis (SEA).

SEA is a protection evaluation technique involving the simulation of faults under various network conditions and prediction of sequential operation of protection elements. SEA-based simulations consider the network changes 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 around the faulted element are recalculated, and their steady-state operation is predicted [9]. The industry-standard short circuit software platforms provide standard macros/scripts to perform SEA-based simulations with the ability to customize simulation parameters [10], [11].

The stepped-events analysis is dependent upon an up-to-date simulation-ready protection model. To reduce the model maintenance effort and timeline, utilities should invest in an automation-based protection modeling solution. Automated protection modeling solutions establish a bridge between the relay settings repository and the short circuit software platform and significantly reduce 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 [12].

Note that while stepped event analysis can help with most of the contingency scenarios, some contingency scenarios dependent upon complex protection modeling (Level 3 as per TABLE I) may require manual analysis. Manual analysis may also be more applicable for SPOFs with a lower system occurrence rate. Automated analysis and related special modeling requirements may not be worth the effort.

*C. Transforming Protection Study Results for Planning Analysis*

The approach described in this paper to perform planning studies for SPOF cases is displayed in Fig. 2. This approach relies on modeling SPOF in protection simulation, running the simulation and listing the operation of breakers, and reproducing those operations in the planning tool. Although manual simulation can be tried for a small number of cases, the simulation of the entire system is impractical without some automation.

There are three major components of the proposed methodology

- Preparing the protection and planning models
- Performing system-wide SEA-based protection simulations
- Translating protection tripping sequence and fault clearing time results into outage files for use in planning simulation tools (contingency conversion)

The approaches to tackle the final step of translating results and creating outage files for planning simulation tools are discussed below.

*1) Protection and Planning Models Alignment*

As discussed in Section III. C. , the contingency conversion process would need alignment between the protection and planning models. This alignment should at least include the bus matching between the two models. It can also be extended to lines and transformers.

The approach adopted by our team was to create a bus mapping table in which every bus from one model is matched to one or more buses from the other model. Then using topology comparison, determine the two- and multi-terminal elements map. To create a bus mapping table, the similarities between the two models—such as numbers, names, or a combination thereof—can be used for automatic alignment as much as possible. Then, missing buses could be aligned manually. It would be advantageous to update either or both models with additional data—such as external bus numbers, etc.—to facilitate automated bus mapping in the future.

*2) Creating Outage Files for Planning Analysis*

There are two types of simulations in planning studies: steady-state and transient. In steady-state analysis, just the list of outaged elements is important, and the sequence and timing of the outages are not included in the outage files since just pre- and post-fault load flow results are simulated. However, in transient analysis, the zero and negative sequence Thevenin impedance at the faulted bus (for single-phase-ground faults), and sequence and the timing of each circuit-breaker operation are critical to be included in the outage files. Specially customized scripts were created to generate outage files for steady-state and transient studies using the bus mapping table and protection analysis results as inputs.

Although the accuracy of bus mapping tables is critical to replicating the breaker operations in the planning model, two other important issues need to be addressed. First, due to differences between the modeled details in each simulation tool, opening a breaker or a set of breakers in the protection model might result in the need to split the bus into two buses in the planning model. Second, planning simulation tools (especially older versions) may not have the option of simulating breaker operation. Therefore, replicating the breaker operation at one of the terminals of a line or transformer may require additional steps of adding temporary (dummy) buses and low-impedance branches to the network.

## V. Conclusion

With the expanded P5 category requirements, the upcoming NERC TPL-001.5.1 standard has warranted greater coordination between protection and planning engineering teams at transmission utilities.

One of the main challenges is identifying and recording the SPOFs in the Protection System. The paper discusses practical strategies for collecting and managing the SPOF data while adhering to the SPOF determination criteria of the standard.

The other key challenges are determining the SPOF based tripping sequence and fault clearing time, and feeding this information into the planning analysis in an efficient manner. The paper discusses an integrated analysis approach that utilizes stepped-events analysis based protection studies, and relies on protection and planning model alignment to generate the outage files for transient and steady-state stability analysis. The advantage of the proposed approach is that it can work with all modern protection and planning simulation platforms commonly used in the power systems industry.

The authors hope that the paper will help protection and planning engineers in understanding the protection evaluation related requirements and challenges of the upcoming TPL-001-5.1 standard, and developing a compliance process based on the needs of their organization.

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## VII. Biographies

**Ishwarjot Anand** is a Principal Advisor at Quanta Technology, where he has worked since 2013. He received his MEng in Electrical Engineering from Ryerson University and his BASc in Mechatronics Engineering from the University of Toronto. 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 many protection engineering automation and data management projects, including automation for NERC PRC and TPL standards compliance and wide-area protection coordination analysis.

**Mehrdad Chapariha** (S'08–M'15) received his BSc and MSc in Electrical Engineering from the Isfahan University of Technology and a PhD in Electrical and Computer Engineering from The University of British Columbia in 2006, 2009, and 2013, respectively. He is currently with Quanta Technology as an Advisor, working on developing 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.

**Gary Webster** is a registered professional engineer with APEGA and has over 15 years of transmission utility experience in protection and control. He received his BSc in Electrical Engineering from the University of Alberta in 2006 and joined Quanta Technology as a Senior Advisor in 2021. His protection expertise includes process development, model management, coordination analysis, settings development, design standardization, and asset management. Gary pioneered a quantified risk-based approach to wide-area protection studies after beginning his specialization in these studies in 2010 and has led the application of this approach to assess and prioritize protection vulnerabilities at more than 300 substations. He also helped to develop industry best practices for short circuit modeling and Protection System coordination with the North American Transmission Forum (NATF).

**Matin Rahmatian** (S’13–M’18) received B.Sc. and M.Sc. degrees in electrical engineering from Ferdowsi University of Mashhad and Amirkabir university of Technology (Tehran Polytechnic), Iran, and Ph.D. degree in electrical and computer engineering from The University of British Columbia, Vancouver, BC, Canada, in 2010, 2012, and 2017, respectively. He is currently with Quanta Technology, Toronto, ON, Canada, as an Advisor, where he is working on power system planning and the development of software solutions for fully automated and automation-assisted studying of power systems. His research interests include power system planning, integration of inverter-based resources into power systems and automation of power system studies.

**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, which has developed many innovative software-based solutions for the power systems industry, particularly in NERC compliance evaluation. Saman specializes 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, 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 lines.

**William Winters, PE** has 20 years of experience in the electric utility industry and Con Edison. He has held positions of increasing responsibility in substation and system operations and engineering, and served as the chief engineer of electrical engineering from 2015 – 2021. Currently he serves as the chief engineer for the protective relay strategy team which is responsible for P&C standards, asset management and technology planning. William earned his BSEE and MSEE from Manhattan College, is a member of IEEE and CIGRE, and is a registered Professional Engineer in New York State.

**Benny Varughese** received his Bachelor of Science in Electrical Engineer from Drexel University and his Master of Science in Electrical Engineering from Manhattan College. He has over 20 years of experience in the electric utility industry. He has held positions of increasing responsibility in substation and engineering. He was a substation Equipment and Field Engineer support Substation Operations; he was also a Protective Relay Testing Supervisor and Manager for Substations Operations. He has also worked as a Commissioning Engineer in Substations working with various utilities; he is currently a Senior Engineer for the Protective Relay Strategy and Implementation group.