Modeling and Simulating Single Points of Failure for TPL-001-5.1 Compliance

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***Abstract*— This paper presents a practical approach to comply with the upcoming TPL-001-05.1 standard by modeling and simulating protection and planning systems in their preferred environments. Firstly, the challenges are discussed, including data gathering for a single point of failure, wide-area modeling of protection and planning systems, and co-simulation of these systems. The paper describes modeling approaches for single points of failure, simulating the operation of the protection system during contingencies and performing stability analysis accordingly. The presented approach is implemented for two North American utility networks and can be expanded to any utilities seeking compliance with the TPL-001-05.1 standard.**

***Keywords*— Protection, Planning, NERC TPL-001, Modeling, Simulation**

I. INTRODUCTION

NERC and other standards gradually require improvement in power system protection, control, and operational performance. Transmission planning performance requirements will be enforced by NERC TPL-001-5.1, which replaces TPL-001-4 (effective July 1, 2023), to ensure that the bulk electric system (BES) will operate reliably over a broad spectrum of system conditions and outages. Seven contingency categories, P1–P7, are defined under these standards that transmission networks should comply with during steady-state and dynamic transients [1].

This paper focuses on category P5 of the standard, emphasizing modeling and simulation challenges and current and future solutions. The P5 category requires both steady-state and transient stability of power systems in events of delayed fault-clearing time due to the failure of non-redundant components of a protection system. This paper continues the work in [2] by expanding modeling and simulation challenges and possible solutions.

A. *Identifying Single Points of Failure*

As per the latest revision of the standard, 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
- 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)
- A single-station DC supply associated with protective functions is 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)
- 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)

B. *New Modeling and Simulating Requirements*

This definition of P5 contingencies requires an upgrade to the existing modeling and simulating approaches, including:

- Identifying non-redundant components of the protective system that can become single points of failure (SPOF) across the entire BES system
- Collecting such data, managing it, and loading it into simulation models
- Simulating both the protection model and dynamics model, simultaneously

In the next sections, the first simulation of P5 under the new standard is introduced, then challenges are discussed, and solutions are provided to tackle the said challenges.

II. MODELING AND SIMULATING APPROACHES

The stability analysis software tools and protection modeling software tools grow separately while serving different departments in the electric utilities. This separation resulted from the traditional analysis paradigms that required minimal interaction between them and the general drive for optimization. However, the power systems are becoming more complicated, and standard requirements are tightening, requiring a unified simulation approach. The TPL-001 SPOF analysis is an example of the new requirements that require a unified solution with both the protection model and transient dynamics considered.

A. *Protection Simulation versus Dynamics Analysis*

A protection system often operates fast after a fault, and the power system's dynamic behavior can be ignored during the clearance of the fault. On the one hand, protection tools are designed with this assumption and calculate the short-circuit currents and voltages accordingly. On the other hand, stability analysis tools assume a simplified protection model with generalized and conservative operation times.

With this assumption of isolation of the dynamic phenomena and detailed protection system operation, the complexity of the model and simulation engine was reduced to a practical extent. As discussed earlier in this section, this simplification is insufficient and inaccurate for the new standard requirements and more complex power systems. Specifically, 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.

In dynamics and stability analysis tools such as [3], [4], and [5], the dynamic model equations are linked to the phasor domain equations using current injection models. In return, the produced voltages are fed back to the dynamic model in a calculation loop. This simultaneous calculation method is an efficient model sufficient for modeling power system dynamics and performing stability analysis for traditional power systems.

In protection analysis tools such as [6] and [7], the protection systems are modeled as an additional layer to the network model. In contrast with the dynamics model, which may only have a balanced network representation. The protection model needs to represent zero-sequence components of voltages and currents accurately. The additional complexity of protection tools is in having enough details of protective relay operation reduced to a steady state to represent a good approximation of relay operation during fault conditions.

As transients and dynamics are not included in the protection simulation, these tools use simplified protective device models that work with steady-state values. After the fault application, their simulation capabilities can be expanded to next-breaker operations, often called events. For such simulation, the tool recalculates the fault currents and voltages right after each network change resulting from a protection operation, then re-evaluates all protective devices with the newly calculated network values to predict the next operation. This process continues until all protective devices have operated or dropped out or the fault current is reduced below a threshold.

Three methods are considered to improve the simulation of system dynamics with consideration of the protection system detailed operation, which will be discussed in II.B, II.C, and II.D.

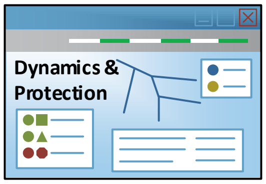


Fig. 1. A single tool capable of simulating protection systems and dynamics.

B. *Option 1: A Single Tool for Modeling Protection and Dynamics*

Integrating the modeling and simulating capabilities of both protection and dynamics in one software tool can significantly help with this standard requirement. A concept is shown in Fig. 1, where there is one model for a power system network, and both protection and dynamics models can be implemented within this tool. This tool is capable of power-flow analysis as well as short-circuit calculation.

There are commercial tools available that can perform multiple types of analysis [5], [4], but they are either not used by North American utilities [5] or do not model protection in detail [4].

C. *Option 2: Protection and Dynamics Co-Simulation*

The idea of having a single tool for both protection and dynamics analysis can be expanded: a third application can be created to use the two simulation engines for protection and dynamics, as shown in Fig. 2. The engines need to have an application programming interface (API) and preferably use the same network model.

Commercial tools are available for modulating the two types of simulation platforms and allow co-simulations [6], [8]. 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.

This approach also 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 [9], [10].

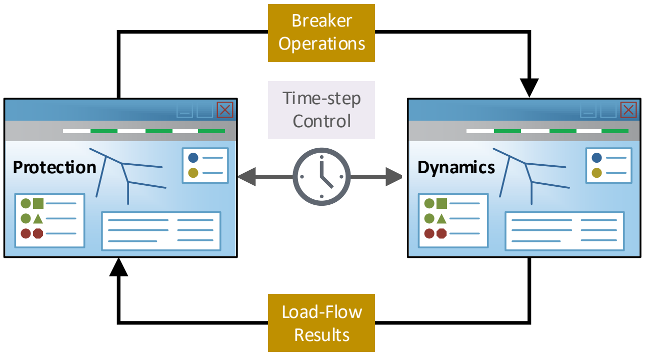


Fig. 2. Linking two individual tools for co-simulation of protection systems and dynamics.

When the two models are not perfectly alighted, a conversion of variables and events from one model to the other must be done at each time step which significantly increases the complexity of the model and the chance of modeling errors and simulation numerical instability. Therefore, such a solution was not selected for this paper.

D. Option 3: Feed-forward of Protection Events to Dynamics

The open-loop solution shown in Fig. 3 is a practical approach for tackling the requirement challenges for the TPL-001-5.1 standard. It is based on feeding protection model simulation results to the dynamic model of the system. This method 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 in this approach. Unlike the co-simulation approach, no additional tool is needed for simultaneous simulation management. The operation of the same system components is translated from the protection system to the planning system and finally fed forward for stability simulation. This can be done manually or automatically, as explained in the next section. Therefore, the authors chose the feed-forward approach as a practical solution [2].

Compared to the co-simulation approach, this is an open-loop 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 for converting results from the protection to the dynamics model.

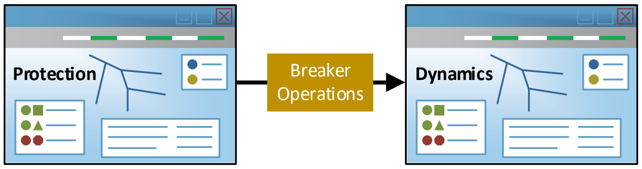


Fig. 3. Feed-forward protection model events to dynamics model.

III. MODELING CHALLENGES AND SOLUTIONS

A. Basic Modeling Requirements

To comply with the standard, the same level of modeling for standard dynamic stability analysis is required. Detailed modeling of breaker configuration can be omitted, though having the same model as protection can improve the process. However, the protection model needs to be modeled in detail, potentially over a wide area where any SPOF is identified. Such modeling is challenging to manage and implement manually and often requires high levels of automation.

B. Modeling Single Points of Failure

1) Identification Phase

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. To ease the burden of the SPOF identification planners may agree that less than one cycle of additional delay could be acceptable if the faster relay is out of service. 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 reviewing single-line diagrams (SLDs), DC schematics, and other drawings.

2) Data Management

SPOF identification can require a large team effort, warranting coordination across different departments—Planning, Protection, Communication, Commissioning, and Testing. 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. Processes must also be implemented to ensure that the SPOF information is updated when impacted by system changes. For example, making the SPOF information a required field in asset management systems ensures that SPOF data is managed indefinitely as team members change.

3) Considerations for Reducing Single Points of Failure

The TPL-001-5.1 standard aims to categorize and define potential contingencies and events that, if they occur, might have severe consequences on the power system's security. One category of contingencies is P5, which is related to the failures or malfunctions of the protection system. It can be inferred from the standard that the protection system upgrade or changes can remove elements from the list of SPOF and mitigate the related P5 contingency. Reducing common types of SPOF is discussed below each component of concern under TPL-001-5.1.

a) Protective Devices

A protective relay is considered a SPOF if no alternative relays provide comparable fault-clearing times. If a different alternative relay exists, evidence of comparable fault-clearing times suffices. Otherwise, a system upgrade can be considered.

b) 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 might be shared and susceptible to failure. This could be especially true for older teleprotection systems, in which upgrading to high-performance modern communication networks should be considered. These systems, such as those using multiprotocol label switching (MPLS) or 5G, tend to have built-in redundancy and a low probability of a loss or delay in service. Still, these systems could be susceptible to SPOF outages, however rare the likelihood is. The least complex approach is typically to eliminate the need to consider communications system SPOFs by ensuring the integrity of the systems is both monitored and reported at a Control Center.

c) 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. A SPOF DC supply failure can simultaneously disable many protection systems. Providing evidence of comparable fault-clearing times under this contingency can be complicated. However, a monitoring and alarm system may remove the DC supply from the SPOF list.

d) Control Circuitry

The control circuitry SPOF and that for the DC supply is usually similarly identified. However, unlike DC supply SPOF, the control circuitry SPOF can be knocked out with a simpler upgrade, such as adding an auxiliary or lockout relay.

4) Modeling Approach

This section describes how to model the four types of system elements identified as SPOF. 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, a certain type of protection modeling may not be required 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.

For cases where modeling of SPOF is required, the outage condition can be implemented directly in the simulation tool or through external controls, as will be explained in III.B.4.a to II.B.4.d.

a) Protective Devices

Normally relays can be readily modeled in protection tools. Some tools allow for protection outage contingency and can easily be used to simulate contingencies where relay(s) identified as SPOF are put out of service. Alternatively, modeling of such relays can be intentionally omitted to simulate the situation where a single point of failure is in effect.

b) Communication Systems

Most protection simulation tools have limited modeling options to include the required details of communication systems for SPOF analysis [11]. Communication systems have many components that can be shared between protection schemes.

Due to the limitation of software tools and the complexity of the simulation scenario, communication SPOF may be modeled with outaging (putting out of service) the entire telecommunication system or the teleprotection scheme. It is important to note that, while most communication systems only negatively impact the faulted line when they are 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 that they protect, except for DCB schemes that need to be associated with each neighboring element.

c) DC Supply

Normally, the protection simulation tools do not have a model for station DC supply. If identified as SPOF, loss of DC supply may be modeled externally by disabling all affected protective devices.

d) Control Circuitry

Like DC supply, the control circuitry cannot be readily modeled in simulation tools but can be modeled externally.

IV. SIMULATING SYSTEMS WITH SINGLE POINTS OF FAILURE

A. Protection Contingency Condition Simulation

As discussed earlier, the P5 category requires the application of an 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 extra high voltage (EHV) and the high voltage (HV) systems and is one of the following types [1]:

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

Most protection tools can simulate the fault contingency and predict tripping sequence and fault clearing time, provided a detailed model of the protection system is present. A simulation is started with fault application.

Enough fault locations should be chosen to determine the worst-case (longest) fault-clearing time. For most equipment types, the fault location can be the buses where they are connected, but for lines, multiple locations can be chosen, as shown in Fig. 4.

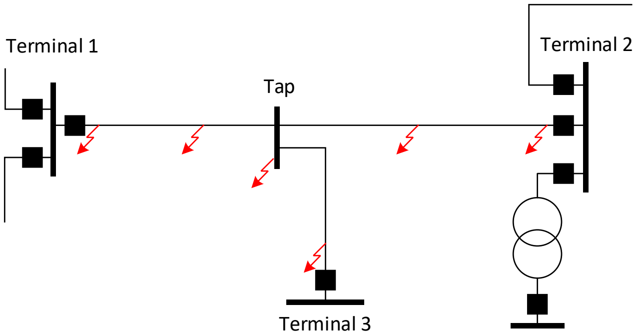


Fig. 4. Fault locations for a transmission line to determine the worst case with the longest clearing time.

Creating and maintaining a detailed protection model requires significant effort. For example, a node-breaker model is required for breaker failure protection modeling and to represent trip coil failure. Still, even with the most detailed protection models available, some SPOFs cannot be assessed by current simulation tools.

B. *Feeding Protection Results into Dynamics Studies*

As discussed in Section II, the feed-forward approach is selected due to the practical limitations of the other two options. In this method, the SPOF is modeled either in the protection model or externally by disabling elements affected by it and then running the simulation.

Before discussing the conversion of protection system operations (breaker openings) to the dynamics model, the differences are described below.

1) *Differences between Network Models in Protection versus Dynamics*

a) *Breaker and Branch Modeling*

Typically, short-circuit models utilize a bus-branch model of the network that limits the representation of each voltage to a single bus within a substation. The bus-branch models are employed due to the lower model maintenance effort, while they include sufficient details to model the commonly performed studies. However, the impact of detailed substation configuration, which may be required for SPOF modeling, cannot be analyzed accurately [12].

Alternatively, the node-breaker model represents the station configuration more accurately but requires greater effort in building and maintaining the model. Software platforms exist to help create and maintain the detailed node-breaker model [12].

b) *Mismatched Buses*

There may be buses that do not have an equivalent in the other model, as shown in Fig. 5. 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.

c) *Breaker Configuration Details*

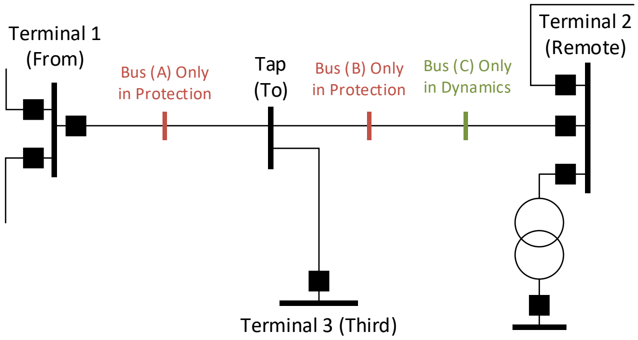


Fig. 5. Differences in the number of buses in protection and dynamics models.

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.

2) *Converting Breakers Operations from Protection to Dynamics*

In the feed-forward approach, the simulation scenario and tripping sequence must be converted to a series of commands for the dynamics model. The simulation results include fault application, breaker openings, and fault clearance based on protection model simulation.

Fault applications and clearance will be repeated in the dynamics model. Whenever an unbalanced network is absent in the dynamics model, an unbalanced fault is emulated as three-phase fault with additional fault impedances [13].

Protection tools commonly model breaker operation at the end of the lines, bus ties (between two buses), shunt elements, and terminals of transformers. Newer versions of dynamics simulation tools for planning studies can also model breakers. However, using a detailed model requires more model maintenance effort and is rare. Therefore, provisions must be made to convert breaker operation to the outage of entire lines or line sections in the dynamics model.

Conversion of breaker operation is straightforward when both network models have matched accurately. Any of the differences mentioned in the previous section requires additional effort for this conversion. This process is called contingency conversion and can be performed manually or automatically. 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.

a) *Branch Matching*

A solution for converting contingencies is creating a branch matching table. There might be one-to-one, many-to-one, or one-to-many matches between the buses of protection and dynamics models. This is a comprehensive solution. However, it is extremely difficult to implement manually, as the number of matches in the table can easily exceed the number of branches in the network.

b) Bus Matching

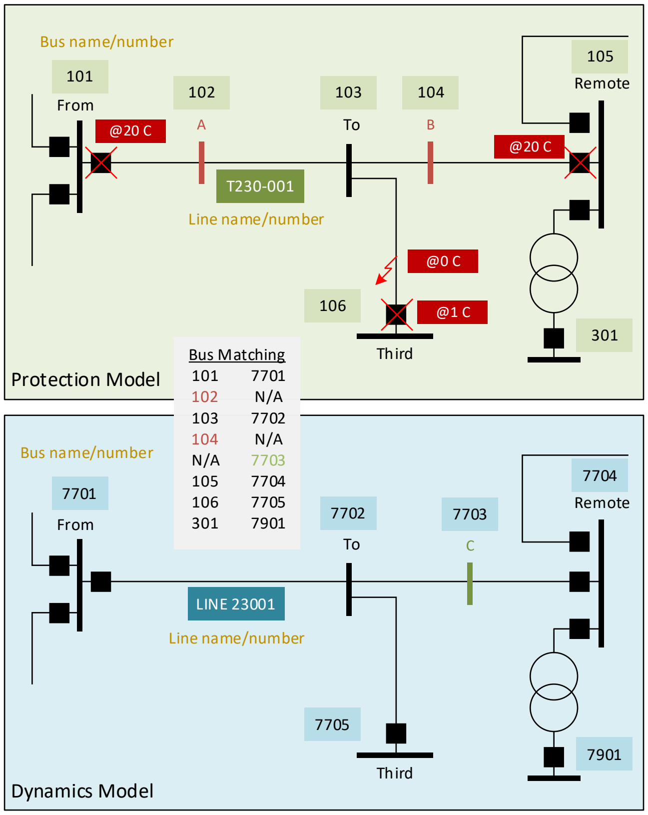
Instead of creating a comprehensive list of the breaker-to-breaker or branch operations, a bus matching table can be used in addition to topological information from both networks. Logic can be designed for topology comparison and determining how a breaker opening in the protection model can be represented in the dynamics model. Using bus matching and topological logic significantly decreases the effort for matching the entire system.

The bus matching table must include a complete map for every important bus and links from one model to one or more buses from the other model. To create one, the similarities between the two models—such as numbers, names, or a combination thereof—can be used for alignment, which can be done automatically. Any exceptions will require manual effort or smarter algorithms.

3) Contingency Conversion Examples

a) With the Presence of Unmatched Buses

Fig. 6, top, shows an example of a fault application and the consequence operation of breakers until the fault is cleared at 20 cycles. Fig. 6, bottom, shows the network in the transient dynamic simulation program. A bus-matching table is provided in the middle of this figure.



Bus Matching

101	7701
102	N/A
103	7702
104	N/A
N/A	7703
105	7704
106	7705
301	7901

Fig. 6. Contingency conversion from protection to dynamics based on a bus matching table.

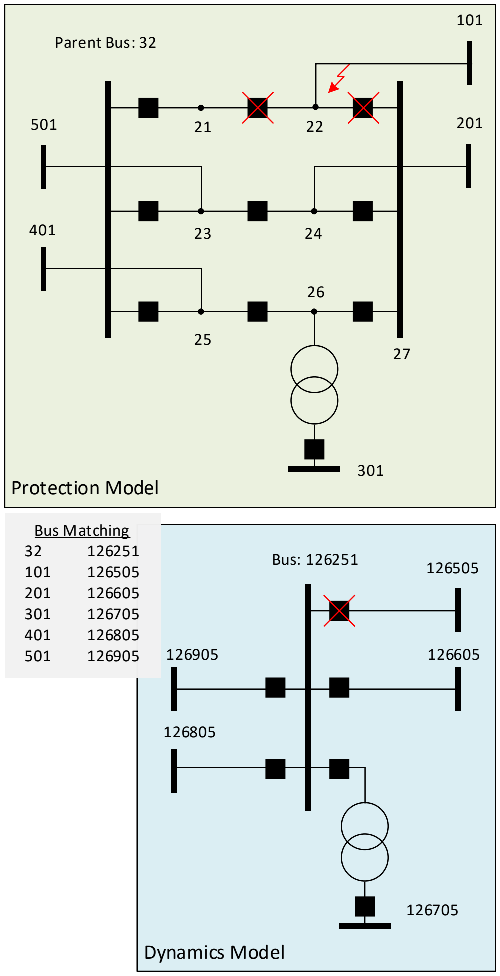
TABLE I. PROTECTION OPERATION CONVERTED TO DYNAMICS MODEL OUTAGE

Protection Outage List		
Event Time	***Protection Branch***	***Dynamics Branch***
@ 1 cycle	106 to 103	7705 to 7702
@ 20 cycles	105 to 104	7704 to 7703
	101 to 102	7701 to 7702

Based on the bus matching and topology comparison, the events (breaker operations) are converted from protection to dynamics model as listed in Table I.

b) With Breaker-and-half Configuration

Fig. 7, top, shows an example of two breakers opening on a breaker-and-half configuration to isolate fault on the branch from 22 to 101. Fig. 7, bottom, shows the same bus with a simple representation of the dynamics model. A bus matching table is provided in the middle of this figure that has a many-to-one relationship from protection to dynamics. Without a full branch matching table, detailed bus breaker operations can be converted to branch openings using the topology and connectivity.



Bus Matching

32	126251
101	126505
201	126605
301	126705
401	126805
501	126905

Fig. 7. Contingency conversion from a breaker-and-half bus configuration to a simple bus configuration.

In the example shown in Fig. 7, the opening of the two breakers in the top, 21-22 and 22-27, isolates the line from 22 to 101. According to the matching table, these buses are matched with 126251 and 126505 in the dynamics model. Therefore, the two breaker operations in the top model are translated to opening the line from 126251 to 126505 in the bottom model. Should there be parallel lines, additional information will be required to identify the correct branch to isolate correctly.

c) With Ring Bus Configuration

Fig. 8, top, shows an example of two breakers opening on a ring bus configuration to isolate fault on the branch from 32 to 101. Fig. 8, bottom, shows the same bus with a simple representation of the dynamics model. A bus matching table is provided in the middle of this figure that has a many-to-one relationship from protection to dynamics.

Like the breaker-and-half configuration, the outage can be converted between the protection and dynamics model using the topology and connectivity after breaker operations.

In the example shown in Fig. 8, the opening of the two breakers in the top, 29-32 and 32-23, isolates the line from 22 to 101. According to the matching table, these buses are matched with 126251 and 126505 in the dynamics model. Therefore, the two breaker operations in the top model are translated to opening the line from 126251 to 126505 in the bottom model. Should there be parallel lines, additional information will be required to identify the correct branch to isolate correctly.

C. Steady-state and Transient Dynamics Stability Analysis

The last stage of SPOF simulation uses the list of faults, delays, and translated breaker operations to run fault-clearing scenarios on the steady-state and dynamics model.

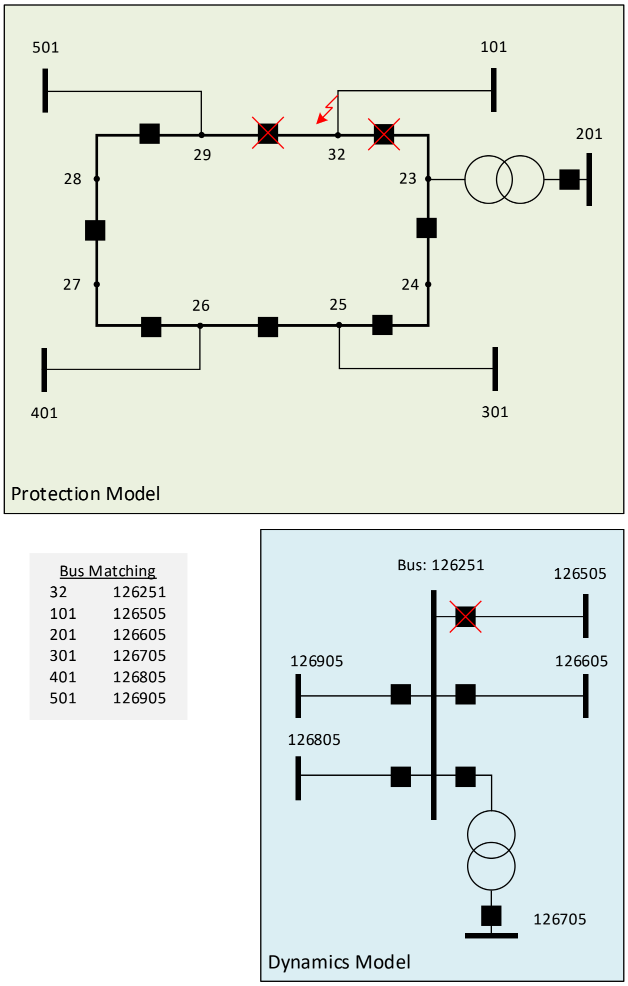
A list of all outaged elements is created for steady-state analysis, and the system's stability after those outages is evaluated. In addition to the list of events and time stamps, the zero- and negative-sequence Thevenin equivalent impedances at the faulted bus should also be recorded for transient stability analysis.

In generating the outage list for the planning tool, two additional conditions should be considered:

- Opening a breaker or a set of breakers in the protection model might result in two isolated buses, which must be modeled by splitting the bus into two buses in the planning models.
- If the breaker model is not supported by a simulation tool, a temporary (dummy) bus, and a small impedance branch may need to be added to replicate a breaker operation.

V. SUMMARY AND CONCLUSIONS

The upcoming TPL-001-5.1 with an expanded P5 category requires more collaborations between the planning and protection departments. Additionally, it warrants new tools to support the simulation of protection and dynamics systems together.



Bus Matching	
32	126251
101	126505
201	126605
301	126705
401	126805
501	126905

Fig. 8. Contingency conversion from a ring bus configuration to a simple bus configuration.

Identifying SPOFs as a requirement to comply with this standard can pose a significant effort initially. This effort will reduce over time by devising new processes and data management systems.

A single network model and one simulation platform capable of modeling and simulating protection and dynamics will be ideal for supporting compliance with the upcoming standard. However, currently, the network models are different between protection and dynamics, and software tools are not used to their full potential or cannot model the interdependency of systems. This paper presents a practical solution to this problem.

The authors have implemented the presented approach for two utility networks. This approach applies to other utility networks regardless of software application tools and data availability.

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VII. BIOGRAPHIES

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William Winters, PE, has 20 years of experience in the electric utility industry and Consolidated 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. He serves as the chief engineer for the protective relay strategy team, 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.

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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, and Supervising Engineer in Power Generation. He is 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 California. He 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. He 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.