Practical Approaches for Digital Twin Representation of Protection and Control Systems

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***Abstract*—This paper presents the considerations, challenges, and solutions for the maintenance of digital twin representation of protection and control systems, ensuring the capacity to support critical needs such as relay settings design, fault analysis, protection performance studies, and compliance evaluations. The annual update processes developed by a major Canadian utility eliminates the typical misalignment of representation, convention, and methodology issues where digital twins are maintained by separate departments. These processes and implementations highlight the critical technical considerations for ensuring the accuracy in representing both system and protection functionality and behavior. The real-world approaches described in this paper are well-suited for sustaining digital twin models that can be utilized for powerful system-wide analysis for settings evaluation and for regulatory compliance.**

I. Introduction

The power industry is facing new and emerging challenges in the engineering, planning, and operation of an increasingly complex electric grid. Brought on by new technologies, regulations, and operational paradigms, these challenges have motivated electric utilities to turn to more capable digital tools and approaches to meet their increased responsibilities. For Protection and Control departments, these challenges have been driven by the following key factors:

- More extreme weather conditions have brought a need for increased reliability and flexibility in protection configurations. Many mitigation initiatives, ranging from enhanced sensitivity settings during periods of elevated risk to proactive disconnection of lines, may require rapid assessments of protection functionality to determine suitability and effectiveness. These studies may require significant reconfiguration of system topologies or assumptions.
- New technologies have opened doors to improved control and operation of the grid. Although they can offer compelling advantages in efficiency and capability, some technologies may change fundamental assumptions that may significantly impact protection functionality. Accommodating new assumptions and operating paradigms may require new protection schemes and scenario testing to ensure reliability.
- Changes in the fault current characteristics due to fundamental differences between Inverted-Based Resources (IBRs) and synchronous generators [1] requires protection models to properly simulate multiple operation scenarios for relay settings assessment.
- The power industry is subject to compliance requirements to ensure reliability of the electric grid. Newer standards have increasingly needed detailed investigations into system characteristics, device configurations, and protection performance, which places additional responsibilities on engineers. These included regulatory standards such as PRC-027, which calls for periodic study of protection coordination, or PRC-026, which requires the determination of system equivalents in a potentially highly interconnected system.
- The complexity of a utility's protection schemes will depend on their philosophy, system layout, and unique requirements. Some transmission lines may have numerous in-line (tapped) transformers with extensive employment of telecommunication-based protection functionality. The study of protection responses for these more complex schemes may require consideration of numerous different functions and communications from multiple devices.

In the drivers above, traditional manual or non-simulation-based approaches to studies and investigation into protection responses may be difficult or impractical for more than a handful of devices. When the need for rapid (and repeatable) assessments is also included, digital solutions may be the only practical solution for addressing these challenges.

Digital twins, virtual representations of the system and equipment, offer a compelling solution to address the need for detailed and flexible protection response assessments at a volume and speed that would be impractical for traditional approaches. These software representations facilitate simulation capabilities that can replicate behavior in the system for both conditions and characteristics, as well as equipment response (such as protection devices). However, the accuracy of any results is heavily dependent on the proper representation of system and equipment, including characteristics, parameters, and logic. Ensuring accurate and up-to-date models in the digital twin is crucial to obtaining valid actionable results.

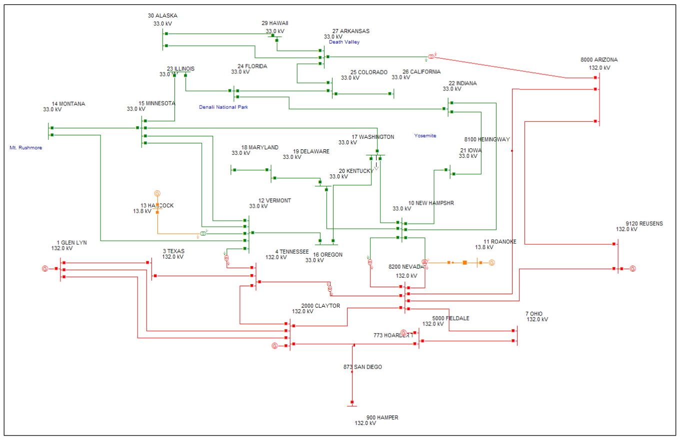

Fig. 1. A digital twin (short-circuit model) utilized by Protection and Control engineers

This paper explores the considerations, challenges, and one major utility's solutions for maintaining an up-to-date digital twin that accurately represents the system and its protection schemes. This exploration draws upon the real-world processes of one major utility to ensure their Protection and Control (P&C) digital twin would be aligned with other departments' own models, reducing the potential for misalignment or inconsistent representation of the system. Within the processes, the approach to large-scale modeling of protection schemes is presented, along with the unique needs and considerations of the utility that affected the design and architecture of the solution. Finally, applications which are supported by the digital twin are discussed, demonstrating how simulation-based capabilities can help address challenges that would be difficult or infeasible to meet using traditional manual methodologies.

II. Maintaining A Digital Twin Representation

As stated in Section I, the viability and usefulness of the results or decisions provided by a digital twin is heavily dependent on the accuracy of data, logic, and representation of the system and equipment. A digital twin model used by Protection and Control engineers typically consists of two main components:

- The system representation, which includes all the buses, substations, lines, breakers, capacitor and reactors, and other physical equipment. This representation provides a foundation on which simulations of faults and other events may be studied or assessed.
- The protection representation, which includes the protection and control devices, such as relays and telecommunications, that make up a protection scheme. This representation provides the responses of the protection and control devices to simulation events, which typically forms the basis behind studies or conclusions.

Establishing both the system and protection representation is feasible in a single, albeit large, one-time effort; multiple organizations have undertaken large-scale modeling efforts to build simulation-capable protection and control models within their short-circuit platform. However, the bigger challenge for utilities has typically been the maintenance of these models throughout both system and protection configuration updates. In addition to the effort needed to implement the updates themselves, the processes for effectively notifying applicable parties that updates are even needed may not always be well defined or coordinated at some organizations.

In parallel to the short-circuit (and protection simulation) model used by protection and control engineers, other departments, such as Transmission Planning, also leverage their own digital twins. Although these models may all nominally represent the same power system, they are typically developed and maintained by dedicated teams in different departments. Different utilities have varying degrees of alignment in model representation between the departments, which can affect update processes and accuracy of each digital twin.

Since the models were typically developed independently of each other, each department may have established their own conventions, representation strategy, equipment inclusion, and even parameter calculation or values (such as line impedances). Differences in calculation methodologies and representation approach result in uncertainty of which model is correct, especially if significant differences are reported across models [2].

The representation strategy for system topologies and equipment inclusions between different departments typically results in inconsistencies between Protection and Control (short-circuit) and Planning (load flow) models. These may be caused by specific application needs (such detailed substation representations [3]) or even engineer interpretation of needed equipment (such as in-line, or tapped, transformers).

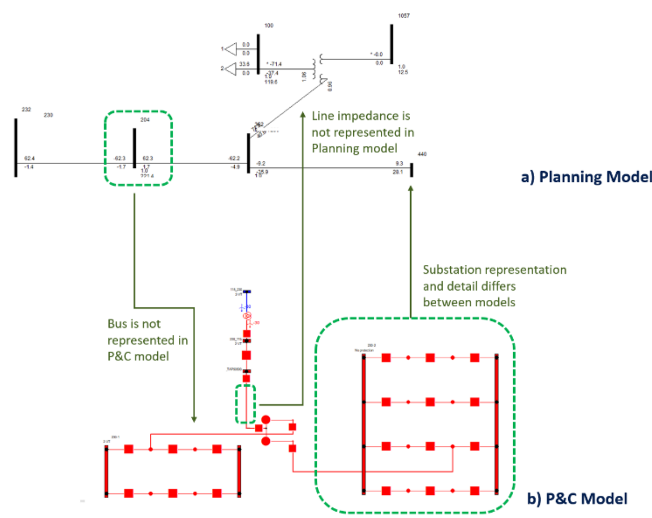

Fig. 2. Differences in representation between a) Planning model and b) Protection and Control model

In addition to the potential for data inconsistencies, each department's use case for their digital twins have dictated what information is populated. As an example, zero-sequence line impedance has no effect on load flow studies performed by the Transmission Planning department but are a critical parameter for ground fault studies performed by Protection and Control engineers.

Finally, each department may have established their own update processes, including notifications to indicate that updates are needed. Coupled with the independent approaches to modeling discussed above, the different models may not be synchronized for updates, resulting in conflicting representations for the same system.

These conflicts may have been masked in the past, but the increasing demand for data across different platforms to drive new analytics initiatives have highlighted the need for consistent data. Even inconsistencies in aspects that do not directly affect simulation performance or results, such as naming and bus numbering conventions, may introduce alignment challenges when referencing equivalent equipment between the digital twins.

Although digital twins can play a key role in the studies and assessments needed within the utility, processes for updating and maintaining the models are needed to ensure they continue to accurately reflect the power systems and equipment. When parallel models are maintained independently by different departments, utilities have encountered a number of challenges in alignment and consistency:

- Communications for updates: notification of system changes that necessitate updates to the model or parameters.
- Alignment: consistent representation of the system between models, including conventions, representation strategy, data, and calculation methodologies.
- Ownership and roles: determination of who owns the underlying data that drives model updates and how conflicts are resolved.
- Department collaboration: communications, collaborations, and agreements on modeling methodology between departments if digital twins are to be maintained independently.

III. Innovative Approach To Maintaining Models

Faced with the challenges in aligning and maintaining their short-circuit and simulation digital twin with the Planning model, the Protection and Control department at a major utility in Canada developed an alternate process to ensure that their short-circuit model would be aligned with the Planning model for a given year. Rather than rely on communications chains and duplication of expertise to independently maintain a long-standing short-circuit model, this utility opts to generate their Protection and Control model on an annual basis, using an updated Planning model as the basis. This approach effectively eliminates system representation conflicts, as well as the risk of missing system updates, since one model is built off the other.

Although this process can mitigate or eliminate many of the concerns discussed in Section II, the re-generation of the Protection and Control model each year does require significant effort to execute, especially in adding simulation-ready protection functionality. To address these needs, the utility has adopted a number of tools and approaches to streamline the process for their engineers.

As stated in Section II, a digital twin model used by Protection and Control engineers typically consists of both a system component and a protection component. This process can be split into two broad stages corresponding to the two components.

A. Establishing a System Model

The starting point for the generation of a new Protection and Control model is the latest applicable Planning model for the given year. Without the need to continuously align or coordinate model updates between different departments, the Planning model is taken as the authoritative representation for the topology and equipment in the system. The generation of the new Protection and Control model is accomplished in the following steps:

- 1a) Conversion tools are utilized to transfer the system topology from the load flow software platform to the new Protection and Control model. This conversion includes all system components including substations, buses, lines, transformers, capacitors, reactors, ground banks, and the connectivity between them.
- 1b) Conversion tools are utilized to transfer both quantitative and descriptive system data such as nameplate or impedance parameters from a Network Model Management repository to the new Protection and Control model.
- 2) Short-circuit studies across both Planning and newly generated Protection and Control models to confirm that both represent the same system, with the same topologies and electrical parameters. This utility has developed automation-based tools to perform these studies and aid investigation into fault current differences, which would indicate mismatch in impedances, connectivity, or equipment representation.

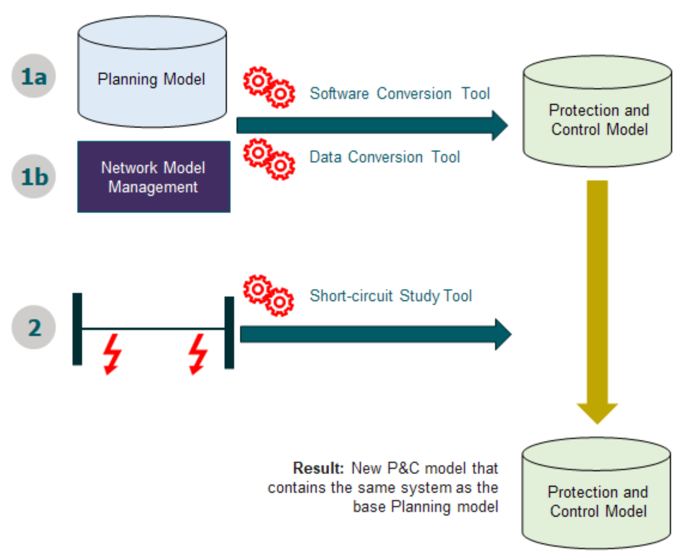

Fig. 3. Process for annual generation of new Protection and Control model: 1ab)generation of new system model and 2) validation of new model

At the end of this stage, a short-circuit model containing a representation of the system and equipment that matches the Planning model would be obtained. As demonstrated during this process, this model would be ready to use for short-circuit studies to aid in fault investigations or relay settings development.

B. Adding Protection Representation

The validated system representation model established in the previous stage would be sufficient to support most tasks performed by Protection and Control engineers using traditional (and predominately manual) approaches to studies. Leveraging simulations for more comprehensive or repetitive assessments of protection performance requires the addition of protection representation into the model, accomplished in the following steps:

- 3) The protection from the previous year's model is merged into the new Protection and Control model through vendor-provided software tools. Since validation is performed on the protection models at the end of the process, this merge provides the new model with validated protection representation up until the previous year.
- 4) With validated protection up to the previous year merged into the new model, the changes and updates to protection since that previous year cutoff point will need to be added to the model. This is typically the most difficult step in the entire process, as protection schemes can be complex, especially with the extensive use of communications-based schemes and in-line (tapped) transformers. This utility leverages automation-based modeling tools to assist in the effort to create simulation-ready protection in the short-circuit model.
- 5) Functionality of the newly added protection is validated based on investigation of expected performance. Tools have been developed to streamline this effort, covering the application of faults according to a systematic test plan and the compilation and reporting of resulting performance.

At the end of this stage, the short-circuit model with validated and simulation-ready protection would be obtained. This model would be ready for the simulation-based assessments and protection performance evaluations that may be required to meet expanding regulatory and reliability needs.

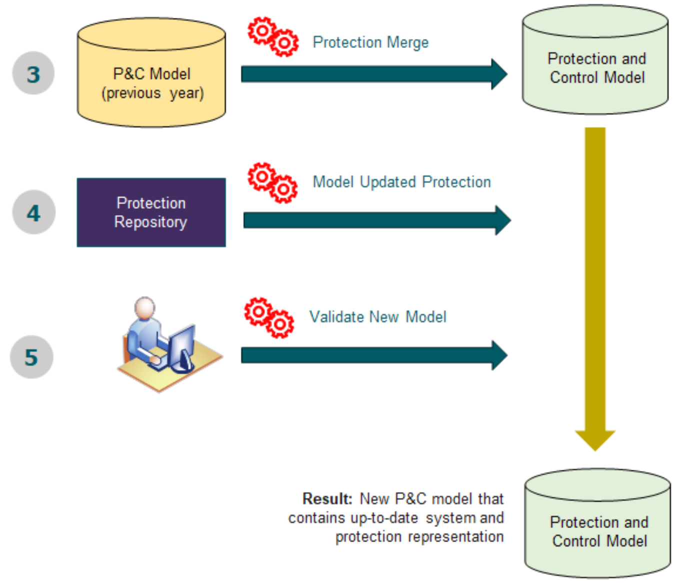

Fig. 4. Process for adding simulation-ready protection to the generated Protection and Control model: 3) transfer of previous year's protection to the new model, 4) creation of new or updated protection, and 5) validation of protection

IV. Protection Update Methodology

For the Protection and Control engineers who developed this annual update process, the modeling of protection representation is the most challenging step of readying the new model. To mitigate these more difficult aspects, tailored automation tools have been established by the utility to streamline the protection modeling process.

A. Challenges in Modeling Protection

The challenges in modeling proper simulation-ready protection representation stem from complexity in both the line topology as well as the protection schemes:

- Most transmission lines have in-line (tapped) transformers called DESNs (Dual-Element Spot Network). The highly interconnected topology of this utility's network means these DESNs serve as a low-voltage bridge to neighboring lines, and thus can provide current during fault scenarios.
- The utility extensively leverages communications-based schemes (both pilots and transfer trips) to improve protection security. Proper representation of these schemes imposes some additional requirements on modeling, including additional information for communications paths and delays, functional elements, and any scheme customizations outside the relay's built-in configuration. The complexity of the utility's schemes actually exceeded the capacity of the default pilot modules built into the software package, necessitating the development of custom modules to accommodate the connections, supervisors, and additional logic.
- Although the utility's protection functionality is generally well standardized, the implementation uses supervisors and functions in addition to the built-in

configuration of the relay itself. This means that building the virtual models in the digital twin requires additional connections, configuration, and even custom modules to accommodate some cases.

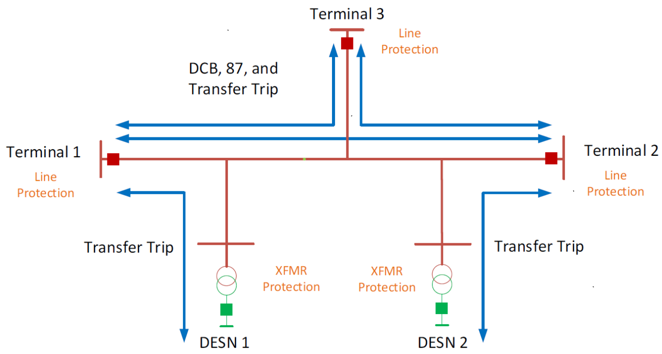

Fig. 5. Typical line topology and protection scheme for the utility

B. *Automation-Based Modeling Tool*

As every other step of the annual model creation process, the utility adopted an automation-based tool tailored to their specific conventions and modeling requirements to address the challenges in creating simulation-ready protection. In addition to creating and connecting the appropriate protection components in the digital twin, this modeling tool also integrated the Protection Repository (for settings data) and the Communications Scheme Database (for communication paths data) to obtain application data. Ultimately serving as a data transformation bridge between these sources and the short-circuit software, this tool enabled the efficient and consistent creation of simulation-ready protection in the Protection and Control model.

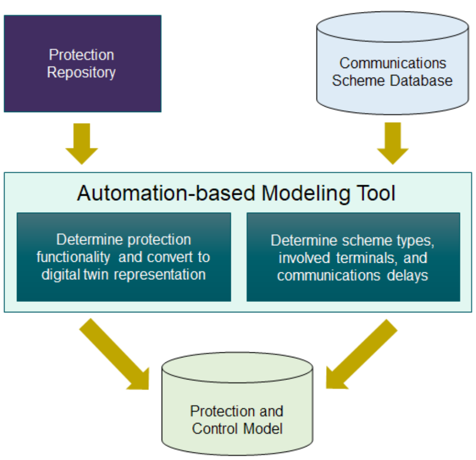

Fig. 6. Expanded logic incorporating additional supervisors for current differential function

The tailoring of this tool extended beyond accommodating the utility's specific naming and modeling conventions. The utility's philosophy and preferences for the role of engineers was incorporated into the tool design. The Protection and Control department relies heavily on the expertise of their engineers, with the expectation that engineers would be the final arbiter of what is implemented into the digital twin. As part of this philosophy, no tool should end up serving as an inscrutable "black box".

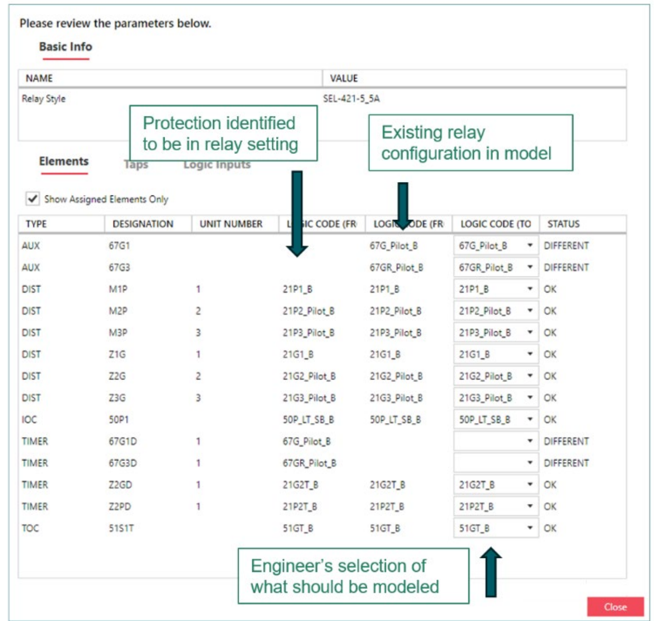

Fig. 7. Break point enabling engineers to override the automatically determined protection functions and specify their own

To accommodate this preference, break points are incorporated into the modeling process, enabling engineers to review and override the decisions made by the automation. One major aspect of this involves the protection configuration. The tool has the capability to automatically identify enabled and tripping functions to determine how to configure the protection in the short-circuit model. This break point enables engineers to review the automatically determined protection functions and assign their own functions if needed. These options provide engineers with ultimate control over the protection representation in the digital twin, while enabling them to leverage the consistency and efficiency advantages of the automation when appropriate.

C. *Supporting Data*

In addition to the relay configuration data that drives identification of applicable functions and their settings that is obtained from the Protection Repository, two additional data sources are required to create functional representation of the protection schemes.

Although the tool can bridge the gap between the protection settings in the repository and creating the appropriate model in the model, an external Translation Table is needed to align repository entries to specific locations in the digital twin. The matching mechanism is designed to minimize the need for modification for relay upgrades "in-place", taking a blanket locational approach for entries in the repository. All devices at a specified substation-line combination in the repository are matched to a location in the model.

New relays with the same combination are automatically matched, reducing the maintenance burden of the table. To prevent non-applicable relays (those that do not need to be modeled) from being matched, a list of permissible devices is maintained to only model certain relay types.

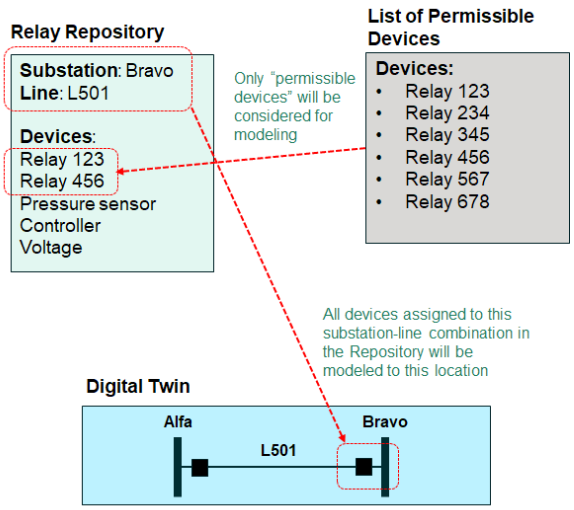

Fig. 8. Translation Table linking of Repository substations and lines to specific locations in the model

For communications-based schemes, the connections between terminals (substations) and their mediums (and resulting transmission delays) are obtained from a separate Communications Scheme database. To associate this additional information with each transmission line, a Communications Table is maintained that states the involved terminals, their connections, and their resulting delays. This persistent table enables schemes to be specified once and retained for the next time the line needs to be modeled (or updated).

D. *Determining Updates*

The annual cadence of the utility's update process brings a significant benefit for determining what protection needs to be updated. Since the merged protection (see Section III.B) is up-to-date to the previous year, the Protection and Control model would need to be updated with all changes (or additions/subtractions) to the protection since the previous year's cutoff.

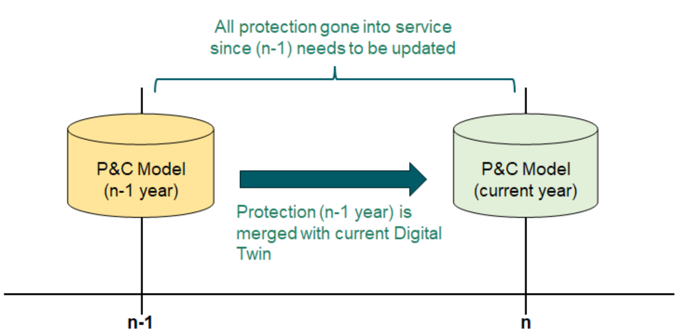

Fig. 9. Identifying updated protection that needs to be added to the Protection and Control model

Identification of these cases is achieved through the metadata assigned to entries within the Protection Repository. Protection with dates-of-completion after the previous year cutoff would need to be added to the Protection and Control model. To simplify this identification, the automation-based modeling tool includes a filter to show only transmission lines that have one or more relays that need to be updated.

V. Applications

Following the annual update process to build an up-to-date digital twin with simulation-capable protection representation, the utility uses this model for two primary applications: supporting relay processes and facilitating compliance evaluations.

A. *Relay Settings Quality*

As part of the relay settings process, the digital twin can serve as a rapid validation of appropriate protection functionality, as well as provide a more detailed assessment of performance. Simple faults can be applied to see protection response, highlighting successful basic functionality.

For more detailed studies, the utility has leveraged further automation-based tools to perform comprehensive testing of relay response and characteristics under different operation conditions and contingencies against a set of acceptable protection guidelines. This capability can pinpoint potential settings issues to protection engineers at the design stage rather than a later stage where addressing settings changes may require more effort (or cost).

B. *Compliance Evaluation*

Although a digital twin with proper protection representation can support multiple different compliance evaluations, PRC-027 is one of the more prominent ones [4]. Requiring coordination studies for lines connected to buses with more than a set amount of fault current variation, this compliance standard is challenging to evaluate without the assessment capabilities of the digital twin due to:

- The large amount of relay and communications logic that must be evaluated at once.
- The need to accommodate different operating principles for different relay types.
- The number of conditions and system contingencies that must be considered and tested to obtain a complete picture of relay response.

The simulation capabilities of the digital twin enable extensive fault current comparisons and wide-area coordination studies to be performed and assessed.

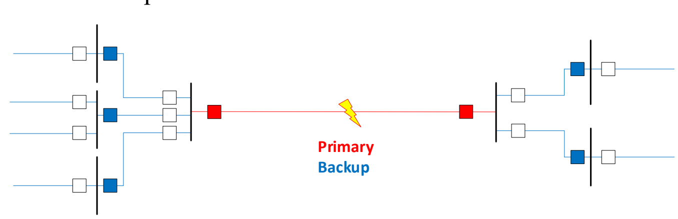

Fig. 10. Faults can be applied in a systematic matter to determine multiple layers of protection response and assess the coordination between them

VI. Conclusion

Digital twins offer a compelling solution to the need for detailed and flexible protection response assessments that traditional manual approaches cannot feasibly accommodate. However, the results and any associated decisions are heavily dependent on how well the models and data within the digital twin represent the actual system under study. Maintaining accurate and up-to-date representation has traditionally been a challenge for utilities, especially when multiple parallel models are owned independently by different departments.

The update process developed by one major utility is one solution to mitigating or even eliminating these alignment conflicts between different models and ensure the Protection and Control model contains an updated system representation. Throughout this process, automation-based tools are leveraged to convert and populate data, merge existing protection models, validate models through short-circuit studies, and create functional representation of complex protection schemes. In addition to tailoring these tools to the technical needs of the utility, the philosophical role of the protection and control engineers is also accommodated with inclusion of engineer review and override points built into the design.

These automation processes, as well as the resulting simulation-ready Protection and Control digital twin enables this this utility to meet their present reliability and compliance responsibilities, and well positions the organization to tackle the new and emerging challenges in planning, engineering, and operating the modern power grid.

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Biographies

Linda (Yilin) Zhao serves as a Protection and Control Engineer at Hydro One Networks Inc, where she facilitates with updating and maintaining protection system models. Her responsibilities include producing protection designs, performing power system studies, and generating settings files to support Hydro One's capital projects. Linda earned her BSc from the University of Calgary and her MEng from the University of British Columbia. She is passionate about advancing the electric utility industry and has been an involved member of IEEE since 2013.

Daniyal Qureshi is a Protection & Control Officer at Hydro One Networks Inc. He specializes in protection system modelling in industry-standard software, studies for the purposes of compliance, and the development of automated solutions for analysis and reporting. Through Daniyal's prior experience as a consultant, he has contributed to relay coordination and sensitivity evaluation tools for numerous utilities across North America.

Suzana Arbana P.Eng., is a senior electrical engineer with over 25 years of expertise in protection, control and SCADA design of power generation, EHV/HV transmission and distribution systems. Her design experience includes utility, commercial and industrial sectors. She has a degree in Electrical Engineering Power System from Polytechnic University of Tirana Albania. Currently she works as the Manager for P&C Engineering at Hydro One where she leads a team of 25 design engineers.

Tim Chang received his MASc from the University of Toronto and has been with Quanta Technology since 2009. His experience at Quanta Technology has covered broad range of aspects from traditional transmission and distribution engineering applications to use of real-time simulators for advanced renewable impact studies. He has been a major contributor to the development of automated processes and applications for data management and engineering studies, including evaluation of NERC compliance standards, software modeling solutions, and wide-area protection coordination studies.

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 a Senior 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.

Jorge Velez is a Principal Advisor at Quanta Technology, where he has worked since 2015. He received his Master of Science in Electrical Engineering from Iowa State University and his Bachelor of Science in Electrical Engineering from the Universidad Nacional de Colombia. He has over 19 years of experience in power system protection, control, and automation. He has worked in the design, settings, maintenance, testing, and commissioning of protective relays for transmission and distribution systems. He has also worked on planning studies, remedial action schemes (RAS) design, fault investigations, protection system modeling, short-circuit and breaker duty analysis, impact studies of renewable energy penetration in utility grids, automated protection coordination studies using CAPE and ASPEN, and network model management.