Detailed Bus Modeling for Enhanced Representation of Power Systems and Network Model Management

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Abstract—**This paper advocates for the adoption of node-breaker (detailed bus) representation in power system models, emphasizing its advantages over conventional bus-branch modeling. Drawing insights from a successful large-scale project with Consolidated Edison, a systematic approach for converting existing bus-branch models to node-breaker models is proposed. The discussion highlights the industry's increasing need for improved network model availability, dependability, and interoperability within the context of Network Model Management (NMM), examining the pivotal role of node-breaker modeling in addressing these needs. Furthermore, we explore necessary Common Information Model (CIM) considerations to integrate node-breaker protection models into NMM applications.**

Keywords—Network model, bus-branch model, node-breaker model, Network Model Management, Common Information Model

I. INTRODUCTION

The accuracy of network models is critical for various types of analysis in power systems, such as relay settings design, relay protection coordination, operational planning studies, breaker duty, and calculating equipment operating limits in general.

Traditionally, due to the significant time investment required and limited computational resources, most utilities have favored the use of simplified bus models (bus-branch models) over detailed bus models (node-breaker models). As a result, most network models employed in various power system applications have remained bus-branch models for many years. Initially, this posed minimal issues due to conventional power system operation. However, with the proliferation of distributed energy resources (DERs), power systems have become increasingly intricate and dynamic, so its modeling requires more accuracy, availability, and interoperability. Node-breaker modeling therefore facilitates the addressing of these requirements by creating a representation of the system that is as close as possible to its real topology and simplifying the analysis of its consequent increased number of contingencies.

Currently, to address the limitations of bus-branch models, engineers rely on external sources for information regarding breaker configurations and other substation equipment data to prepare the model for studies. However, this practice has evolved into a time-consuming task every time a new study is required. With the rising frequency of DER additions to the network, engineers are spending substantial time preparing models for studies, contradicting the original rationale for adopting bus-branch models. Moreover, the increased need for advanced system analysis such as bus or breaker contingencies for relay settings design and regulatory compliance studies makes bus-branch models highly error prone mainly due to the manipulations required to split buses and therefore inefficient. A solution to mitigate this inefficiency is the adoption of node-breaker models as the base case. Although node-breaker modeling adds complexity to the graphical visualization of the network, its benefits in enhanced visibility, accuracy, and interoperability of the model are fundamental for today's system needs.

This paper will first outline the advantages of node-breaker modeling compared to simple bus modeling. It will then describe an overall strategy for implementing detailed bus modeling in a protection simulation platform in more than 100 substations of Consolidated Edison's power system. The paper will address challenges associated with the implementation of this strategy, sharing lessons learned and suggesting improvements to the utility's network modeling guidelines. Finally, the paper will provide an overview of how the implementation of detailed bus modeling in protection and planning models is a strategic foundational step for Network Model Management applications.

II. DETAILED BUS (NODE-BREAKER) MODELING

This section discusses the relevant background for node-breaker modeling, along with its advantages and current use in the power industry.

A power system network for analysis and simulation purposes can be represented in two types of models, namely, the bus-branch model (Fig. 1) and the node-breaker model (Fig. 2). Node-breaker models, also sometimes referred to as breaker-oriented models, are detailed bus models that are represented by buses as nodes and elements such as breakers, switches, branches, and shunts modeled individually and connected via these nodes. These models may range from basic topological arrangement of the substation equipment to a fully built-out substation representation as they appear in operational single-line diagrams and/or in the field, making them ideal for complex power system analysis purposes.

Bus-branch models, also sometimes referred to as bus-oriented models, are simplified bus models that are considered abstract models that are derived from node-breaker models. They are typically represented by a single bus at each voltage level for each substation and branches for transmission lines or other elements connecting these buses. While bus-branch models are sometimes sufficient for specific studies such as power flow and contingency analysis, the lack of information regarding the network topology introduces inefficiencies when special analysis such as bus section faults or breaker failure conditions must be conducted.

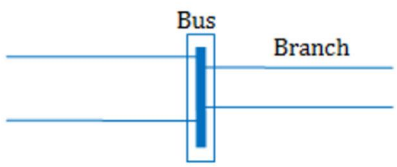

Fig. 1. Bus-branch model diagram (Source: PSS®E 34.1 Operation Manual [1])

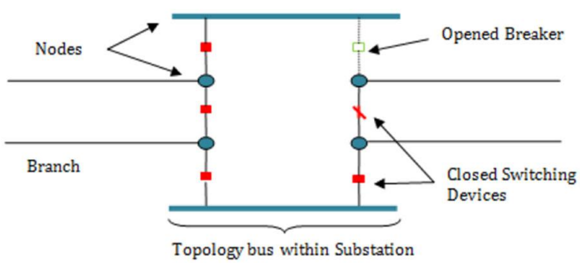

Fig. 2. Node-breaker model diagram (Source: PSS®E 34.1 Operation Manual).

There are numerous advantages to employing node-breaker models in the literature, including, but not limited to [2]:

- Enhancing visibility into substation configurations and equipment, including switching statuses of circuit breakers and disconnectors as they appear in the field.
- Enabling seamless integration of topological changes to the network, such as bus splitting, by adjusting the statuses of switching devices, eliminating manual effort.
- Containing sufficient information for power flow software to use automation to create and simulate complex contingencies such as stuck breaker contingencies.
- Facilitating simulation of breaker failure protection schemes for individual breakers in the substation.
- Assisting breaker duty assessment by providing individual currents flowing through the breakers, considering only the sources that are physically connected to them.
- Enabling the implementation of bus differential relay settings checks for gross setting errors such as current transformer (CT) connections or improperly defined protection zones.
- Allowing for greater interoperability between network model data used in operational studies and planning studies when representing existing topology.
- Allowing for better model alignment and exchange with other simulation platforms, such as energy management system (EMS) system models.

Traditionally, node-breaker models are primarily used in system operations for real-time system visualization purposes. In contrast, bus-branch models are used for planning and protection studies. The limitations of bus-branch models become evident when conducting contingency analysis studies. Replicating various outage conditions, such as node and breaker failure contingencies and bus splitting actions, requires extensive manual effort. As more contingencies are studied in this manner, complexity increases, making this process increasingly prone to human error, inaccuracies, and time inefficiency.

Aiding in the transition from bus-branch models to node-breaker models, power system software and tools have improved to provide detailed bus modeling capabilities. Currently, many power system analysis platforms, as cited by NERC, support node-breaker modeling [3]. Some research has also been conducted on various algorithms surrounding node-breaker models, such as network topology processing impedance. These methods are used for converting a node-breaker model into a bus-branch model. Additionally, the space tableau approach, an optimization technique, is used for transient stability simulations in node-breaker models [4].

III. Methodology To Convert Bus-Branch Model to Node-Breaker Model

In this section, we will illustrate the methodology to convert an existing bus-branch network model to a node-breaker by breaking down the steps taken in the Consolidated Edison project. Lessons learned will also be presented as a reference to warn readers about what can be found tricky to deal with if related preparation is lacking at the beginning of the conversion process.

A. Modeling Conversion Breakdowns

Before the conversion, there are two critical tasks to take on. One is to collect the drawings and technical documentation needed for the target substations, and the other is to come up with needed naming conventions. Once we have all the drawings collected and naming convention guidelines created, the engineer can start working on the model update. During the model update, it is important to realize that it is not just the buses that need to be changed, but there are other modeling aspects impacted in the process and thus need to be updated. An example are the specific attributes predefined by the simulation software to properly recognize a node-breaker representation or the addition of transductors if protection modeling is required. To ensure a functional protection system model with the updated network model, new CTs and VTs also needed to be created and connected to corresponding relays. It is also important to review and reconfigure what breakers are being tripped by relays in the short circuit model, as more breakers are introduced naturally in this process.

The bus-branch to node-breaker conversion steps are summarized as follows:

- Convert from straight bus to detailed bus according to drawings, following modeling software instructions. In this process, new buses and new breakers are added to the network model.
- Reterminate elements (lines, transformers, capacitor banks, generators, and other shunts). In this step, the elements must be connected to their corresponding buses within the detailed bus structure.
- Create new CTs, VTs, and CT summation points for protection modeling.
- Reconnect CTs, VTs, and CT summation points to protective relays.
- Define what breakers to open due to relaying operations.

The detailed bus model conversion presents a system model as complicated as it is beneficial. It is critical to ensure that the extra modeling details introduced in the conversion remain correct and functional in studies. A simple yet effective way to do quality assurance on the new model is to simulate a few faults and check if the correct relays clear the faults. Overtripping or undertripping issues should be analyzed and corrected as they are discovered.

B. Lessons Learned

There are relevant items to consider when implementing bus-branch to node-breaker modeling:

a) Identify Study Dates: Define a clear-cut date for models of new substations or new constructions and collect corresponding drawings as the base of modeling. There are always new substations being built and new construction changes happening in existing substations or being planned for the next few months or years. A common question is how far in the future the model should cover. This often depends on whether the new or planned substation has enough details and if there are envisioned studies that will need detailed substation modeling. For the Consolidated Edison node-breaker model conversion, we selected all existing substations and future substation upgrade projects with an in-service date earlier than the next six months. Any substation upgrades beyond the defined cut-off date were required to be reviewed and included on a case-by-case basis. Features to add layers to the base case model in the simulation platform were utilized to differentiate between in-service and future substations configuration projects.

b) Define Scope for Protection Modeling: The node-breaker modeling of power equipment such as lines, transformers, and shunts should follow the exact topology of the system as shown in the single line diagrams and other verified sources of data. However, when protection modeling is added, defining a suitable scope of what to model and what not to model is recommended. This requires definition of a clear set of use cases for which the network model will be used for. For example, when implementing node-breaker in protection models and adding the relaying model layer to it, there are spare CTs, metering CTs, and leaking CTs that are typically not used for protection-related simulations hence its modeling will not provide added value to the model. On the contrary, this can increase the complexity and the size of the model and make it difficult to maintain.

c) Define Naming Convention: Define an inclusive enough naming convention that considers all possible scenarios. The data quality of any given model often limits the quality of the model and the potential usage of automation. To aim for a model with clear and consistent data not only for manual but also automated studies and data analytics, one should plan a highly consistent naming convention. This requires considering the "worst-case scenario" for all aspects of data and how they can fit within the limits of the simulation platform. For example, protection model platforms might allow a very short and unique name for CTs as at a given substation. With node-breaker modeling, there will be many CTs and auxiliary CTs added to the model and character limitations of the simulation platforms can introduce challenges to assign these CTs with a unique name.

IV. Applications of Node-breaker Modeling

When using node-breaker modeling for power system studies, it is important to open it to different types of studies that can leverage this way of representing the network. In short-circuit or protection models, node-breaker modeling is very instrumental to support studies such as breaker failure, NERC TPL and PRC compliance, fault clearing time, and breaker duty assessments.

For breaker failure analysis, consider the network shown in Fig. 3 showing a common ring bus configuration is to connect transformers to the bus without a dedicated high-voltage breaker. For the fault illustrated in low-side of transformer T1, if there is no transfer trip to the remote end for a breaker failure condition on breaker 1, the remote line protection zone 3 is relied on to clear faults on the low-voltage winding of the transformer. The remote line protection zone 3, which is set to detect faults on the low-voltage winding of the transformer, will typically be set with a large delay to maintain coordination.

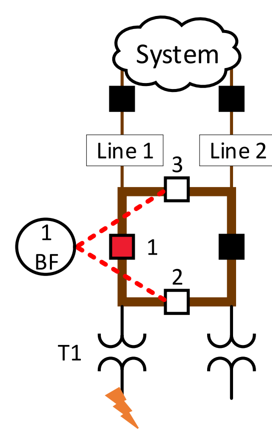

Fig. 3. Node-breaker model example for breaker-failure analysis.

If breaker 1 fails, the breaker failure protection will trip local breakers 2 and 3. This will result in the ring being split such that line 1 is isolated with T1 and the fault, and line 2 is connected to T2. Until the remote line 1 delayed protection trip, the system configuration cannot be represented in a bus-branch model unless a manual bus split is performed. The node-breaker modeling provides a practical way to represent the topology of the network under this breaker failure condition and allows a straightforward evaluation of remote terminal protections for both reach and operation time.

Another use case where the node-breaker modeling becomes very practical is to evaluate simultaneous breaker failure conditions. Although this condition might go beyond typical relay settings criteria, NERC TPL-001 P5 control circuit contingencies can require an analysis of these type of scenarios.

Fig. 4 shows a ring bus configuration with a fault being applied to one of the bus sections. The line 1 differential protection protects the bus section. Both trip coils of breakers 1 and 2 are supplied by the same DC panel, which falls under the control circuit contingency definition from TPL-001. These breakers are inhibited in the simulation software to prevent them from opening. Breakers 1 and 2 have breaker failure protection, which will trip adjacent local breakers only. After the line 1 remote differential protection and breaker failure protection operate, the remote zone 2 protection for lines 2 and 5 must trip to clear the fault. The system configuration at this point in the simulation would not be representable in a bus-branch configuration because the ring bus has been split into two sections. Lines 2 and 5 would be isolated with the faulted side of the ring, while lines 3 and 4 would be isolated on the opposite side. TPL-001 requires the breaker operation sequence from the short circuit analysis to be used for stability analysis. The ability of node-breaker models to split the ring bus allows for more accurate stability analysis to be performed.

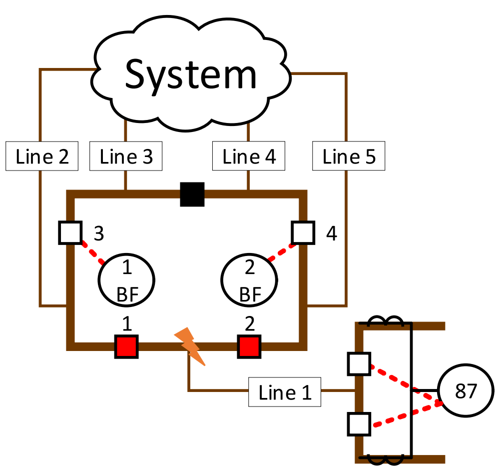

Fig. 4. Simultaneous breaker failure contingency

V. Node-Breaker Integration To Network Model Management

Electric utilities are experiencing a remarkable number of transitions with increased penetration of distributed energy resources, increased demand due to electrification and decarbonization initiatives, and the increased emphasis on integrated transmission and distribution systems for greater operational efficiency. Effective management of the network models, ensuring accuracy and timeliness, is crucial for the reliable design and operation of power systems, especially during this transitional period. Therefore, the implementation of NMM solutions has become highly relevant across the industry in recent years as a response to the aforementioned challenges.

The concept of NMM primarily covers the tools and processes necessary to ensure and maintain a unified representation of the network across different applications for power system analysis and operation. NMM platforms should constitute a single source of truth for the power system model, facilitating network model availability, dependability, and interoperability (Fig. 5).

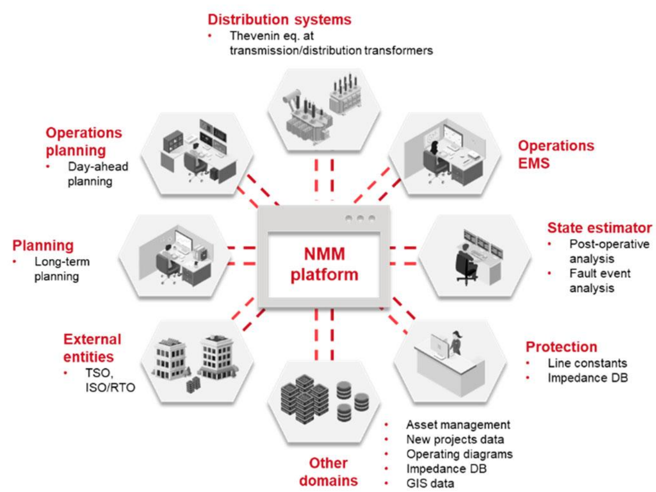

Fig. 5. Network Model Management concept.

Node-breaker modeling is fundamental for the implementation of the base case network model in NMM applications as it provides the most accurate representation of the topology and connectivity of the network. The integration of node-breaker models into NMM applications is a task that demands a thorough methodology to achieve consistency and interoperability. As different power system applications have different data structures to store node-breaker attributes, data adaptors are required to achieve interoperability between NMM platforms and these applications. Although data adaptors can be developed to achieve interoperability between power system applications (Fig. 6), the overall NMM concept strives for interoperability between power system applications and a centralized NMM platform that serves as a single source of truth for network data (Fig. 7).

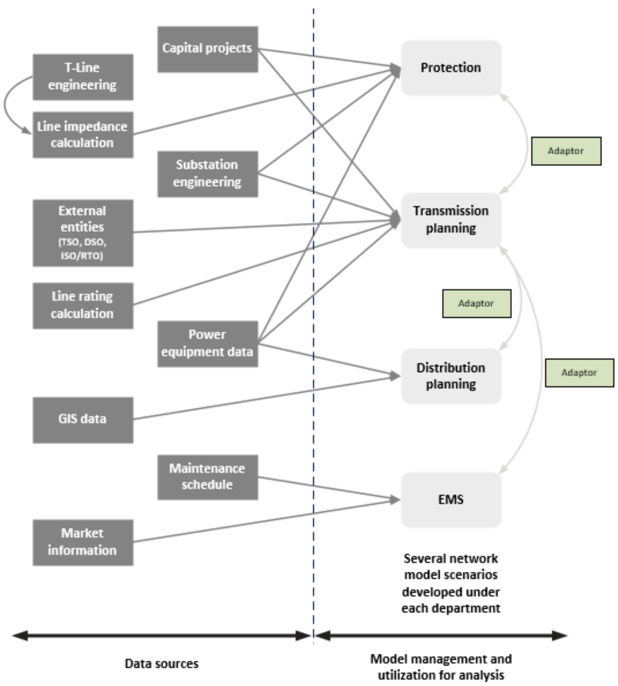

Fig. 6. Traditional source data and Network Model Management approach.

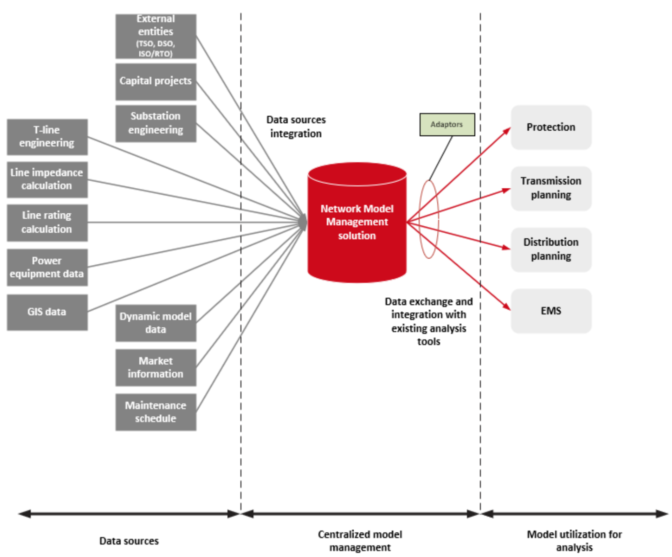

Fig. 7. Centralized source data and Network Model Management approach.

To standardize the interoperability between network models, the IEC developed the Common Information Model (CIM) with an electric utility-specific information structure to organize shared data. Instead of having adaptors with customized translations of network data between applications, the CIM acts as a logical model in the middle of applications (semantic model), allowing translations between applications and the centralized NMM platform.

Regarding the network model representation and its connectivity, the CIM supports both views of the substation data: node-breaker (via the Topological Node class) and bus-branch (via the Connectivity Node class). These two classes have similar behavior while representing different levels of detail of the network. Therefore, network models can be displayed as a bus-branch if required or preferred for certain analysis such as off-line transmission planning studies, but also displayed as a node-breaker if studies as the ones described in section IV are required.

The implementation of NMM solutions requires the establishment of a network model base case built based upon existing model in the EMS, planning, protection, or other application within the utility. Regardless of where utilities decide to start implementing NMM solutions, the development of adaptors between applications and the centralized solution is one of the main challenges. Particularly, when implementing node-breaker modeling, other challenges might arise since not all the power system applications in the market are fully developed to model node-breaker and to store the corresponding data following standard structures such as the CIM. This could represent a major roadblock towards NMM solutions and should be considered when defining implementation road maps.

VI. Conclusions

This paper advocated for the implementation of detailed bus (node-breaker) network, citing its numerous advantages over conventional simplified bus (bus-branch) models. To this end, a systematic approach has been proposed to address the challenges associated with the model conversion from bus-branch to node-breaker in a short-circuit program. Finally, as power systems continue to change at a rapid scale, the paper argues that the integration of node-breaker modeling into NMM solutions is becoming increasingly important in ensuring the resilience and efficiency of power system operation and design.

VII. References

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VIII. Biographies

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.

Naveen Manikarnika received his Bachelor of Science in Mathematics from New York University, his Bachelor of Engineering in Electrical Engineering from Stevens Institute of Technology, his Master of Engineering in Electrical Engineering from Stevens Institute of Technology, and his Master of Business Administration from New York University. He joined Consolidated Edison in 2012, and has held positions of increasing responsibility in substations and engineering. He worked as an engineer in the Technical Applications Group, creating test plans for microprocessor relays and providing commissioning support. He then transitioned to Bronx Protective Systems Testing (PST) as a supervisor, where he supervised a group of technicians and was responsible for the maintenance and commissioning of protective relay and SCADA systems for all substations in the Bronx. He is currently the Section Manager for the P&C Asset Management and Strategy team.

George Goddard received his B.S. degree in electrical engineering from the University of Michigan. He joined Consolidated Edison's Control Systems Engineering team in 2019, working in the relay protection analysis and system support section. His previous experience is with relay protection and design in the Michigan transmission and distribution system.

Jorge Vélez 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 18 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, protection database management, short-circuit and breaker duty analysis, impact studies of renewable energy penetration in utility grids, and automated protection coordination studies using CAPE and ASPEN.

Ishwarjot Anand is a Principal Advisor, Power Systems Modeling and Data Analysis Director at Quanta Technology. He received his master's in electrical and computer engineering from Toronto Metropolitan University and his bachelor's in mechatronics and robotics engineering from the University of Toronto. He has expertise in computer-aided modeling and analysis of electrical power systems and protection systems for transmission and distribution networks. He has led several protection engineering automation and data management projects, including automation for NERC PRC and TPL standards compliance. Ishwarjot has worked on large-scale, wide-area protection coordination studies for AltaLink, Xcel Energy, and National Grid Saudi Arabia. He has also worked on renewable integration and automation projects. Additionally, he has extensive experience analyzing mechanical systems, applying manufacturing technologies, improving industrial processes through lean methodologies, and project management.

Zaeem Amjad is a Consultant II at Quanta Technology. He graduated with a bachelor's in electrical and computer engineering from the University of Toronto and specialized in energy systems and systems control. He is currently pursuing a master's in electrical and computer engineering at the University of Toronto. He has supported power system modeling and data analysis projects, including detailed bus modeling in CAPE, protection engineering automation in ASPEN, and digitizing substation equipment and EM relay settings. Previously, he has worked in the nuclear industry supporting I&C design, field engineering tasks, and project management.

Justin Schmidt, PEng, is a Senior Advisor at Quanta Technology. He has over 10 years of experience in the electric power industry. He has expertise in short-circuit modeling of power and systems, protection philosophy, CAPE macro design, and power system process automation. Justin has been involved in and led several wide-area protection coordination studies during his time working at a utility since 2012. He has overseen maintaining short-circuit models for the utility by performing model merges and updating source information. He has also been involved with protection settings design, including distance, overcurrent, pilot schemes, undervoltage, and differential protection.

Xinyang Dong is an Advisor at Quanta Technology. She graduated with a master's degree from North Carolina State University's Department of Electrical and Computer Engineering in 2015. She has worked at Quanta Technology since 2016, where she has gained extensive experience modeling protections and performing protection studies like wide-area coordination, settings evaluation, feeder studies and relay coordination, fault location identification, and short circuit analysis using CAPE, ASPEN, and CYME. She also has extensive experience with automating studies using various programming languages. She is a project/product manager, managing and leading large projects, interfacing with customers to understand their needs, and helping to build the best-suited automation solutions.