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Simulation Models of Line Protection Incidents with Solar Power Generation

Leila CHEBBO*
University of Connecticut
USA

Genesis ALVAREZ, Daniel K. RIDENOUR,
Katelynn VANCE
Dominion Energy
USA

SUMMARY

The high penetration of inverter-based resources (IBRs) into the power grid is changing system dynamics and affecting existing protection schemes. To understand IBRs' fault response and to avoid a protection maloperation, this study presents the main factors contributing to protection challenges in the modern power grid. It describes a protection incident associated with the interconnection of IBR facilities in the Dominion Energy network. It also shows simulation models reflecting the solar-based system within Dominion's network using different fault analysis tools, such as ASPEN OneLiner™ and Real-Time Digital Simulator® (RTDS). This paper compares the real incident records with the simulation results to determine the most suitable fault analysis software model for system protection engineers to use. Simulation results show that RTDS provided the highest level of system representation accuracy, where the mean difference between the actual records and real-time simulation was 3%. A comparison of two versions of ASPEN OneLiner™ showed that the newer version, which models photovoltaic (PV) sites as converter-interfaced resources, demonstrated better representation of the protection incidents.

KEYWORDS

Line protection, relay, renewable energy, solar power generation, inverter-based resources, real-time simulation

leila.chebbo@uconn.edu

I. INTRODUCTION

The electric power grid is rapidly evolving to include renewable energy sources such as solar and wind. Solar power generation has seen exponential growth in the past two decades. The total annual electricity generation from solar generators in the U.S. has increased from about 493 GWh in 2000 to about 145,598 GWh in 2022 [1]. Solar plants are connected to the electrical grids through power electronic converters, as shown in Fig. 1; thus, in this paper, they are referred to as inverter-based resources (IBRs).

From the power system perspective and apart from their intermittent nature, IBRs behave differently than traditional generation facilities, which imposes new challenges in grid planning, operation, and protection [2]. For example, synchronous generators' response to a fault in the power system is based on the physics of the rotating machine, which is well-defined for grid protection engineers. However, IBRs use power electronic controls to support grid reliability and instantaneously respond to grid disruptions and faults [3]. Consequently, an IBR's different fault current response affects our current practices for applying and setting protective relays [4]. Traditionally, relays have been selected based on the fault current characteristics of a synchronous generator (SG)-dominated system, i.e., high amplitude and inductive short-circuit current. On the contrary, the fault current induced by the IBRs is characterized by:

- **Low fault current amplitude:** The amplitude of the continuous fault current has a nonlinear dependence on inverter terminal voltage and is typically low since it is constrained by the converter current limiter to values close to the nominal load current [5].
- **Lack of fault sequence quantities:** Inverter fault current does not include a zero-sequence component. Furthermore, the negative sequence, which depends on the inverter control algorithm, is typically insufficient [6]. The lack of negative- and zero-sequence currents level makes the fundamental principles of power system protection unfeasible and causes maloperation of the protection system [6], [7].
- **Variable fault current power factor/phase angle:** The fault current of IBRs has a variable phase angle depending on the control scheme and the amplitude of the inverter terminal voltage. Further, in contrast to a SG whose fault current is predominantly inductive, the fault current of an IBR may be either resistive, inductive, or capacitive. The control mode considerably impacts the angular relationship between on-fault voltages and currents near the IBR, which is required by some protection functions (e.g., directional elements) for correct operation [8].
- **Variable fault current duration:** The amount of time an inverter can continuously inject overcurrent into the grid during a fault depends on the inverter control and thermal limits of the power electronics [9].
- **High rate of frequency change:** IBRs have no inherent rotational inertia. Hence, large-scale integration of IBRs is expected to increase the rate of system frequency change following significant system disturbance. Furthermore, faster power swings are expected under high shares of IBRs due to the reduced inertia [10].

Thus, with the high integration of renewables into the power grid, the existing protection schemes can be affected and experience malfunctions due to the changes in fault characteristics [3]. It is crucial to understand how IBRs react to fault conditions so that proper protection settings can be set to avoid a protection maloperation or a failure in grid operation.

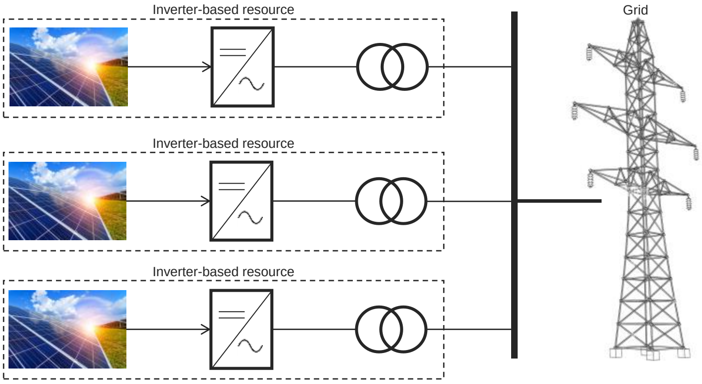


Fig. 1. Inverter-based resources connection to the grid.

Considering these requirements, this work contributes to the current research in making the modern power grid more robust, efficient, and reliable. This paper describes protection challenges associated with the interconnection of IBR facilities in the Dominion Energy network, which can be extrapolated to any network. It also presents accurate simulation models reflecting the system using different fault analysis tools such as ASPEN OneLiner and RTDS. A comparison between the real incident records and the different simulation results is evaluated. This study determines the suitable fault analysis software model for system protection engineers.

The structure of the paper is as follows. Section II presents a description of the protection incidents happening on the grid after the integration of a photovoltaic (PV) system and examines the main reasons for line protection relays malfunctions. Section III discusses the different simulation models in ASPEN OneLiner and RTDS. Section IV shows the simulation results and the comparison with the actual fault event records. The conclusion and recommendations are finally given in Section V.

II. PROTECTION INCIDENT DESCRIPTION: CAUSES AND EFFECTS

The Dominion Energy network has experienced protection malfunctions associated with the interconnection of IBR facilities. Fig. 2 illustrates one of the protection incidents that happened on the grid and cause damage to power system components. Due to the different fault current characteristics of IBRs, the protective relays A and B, which are set based on the short-circuit characteristics of SG-dominated power system, are not correctly detecting the faults. Consequently, the short-circuit fault current from the solar sites is flowing towards the fault and damaging some power system components.

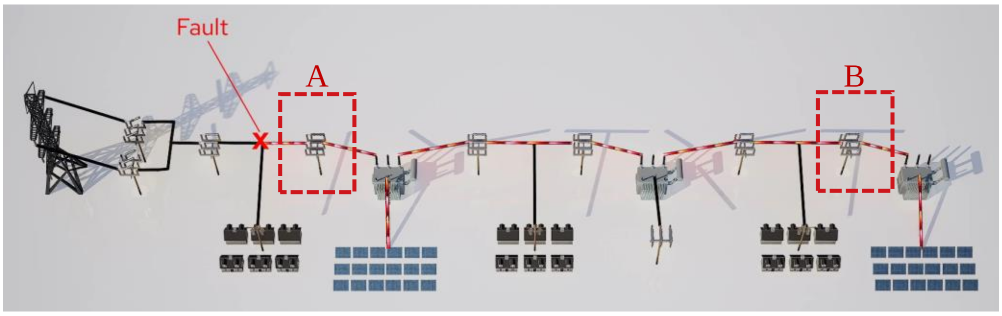


Fig. 2. Protection malfunctioning incident in Dominion Energy network.

The academic literature discusses the reasons for line protective relays malfunction in the modern grid. Table I summarizes the main expected protection challenges caused by the IBRs.

TABLE I
Summary of the line protective relay challenges

Protection Function	Expected Protection Challenge in modern grid	Ref.
Line distance protection	• The low fault-current amplitude and lack of supervising current lead to failure in the relay trip. • The change in source impedance leads to unpredictable and inconsistent dynamic expansion of the mho circle, which reduces the reach accuracy and increases the risk of over- or under-reach.	[11], [12]
Memory-polarized zero sequence directional protection	• The lack of inertia and fast control response time cause a shift in the phase angle of voltage during the fault, which caused an incorrect directionality decision.	[13]
Negative sequence based directional ground fault protection	• The lack of negative sequence contribution by IBRs leads to a low level of supervising current, making the element not assert. • Changes in phase angle under IBRs leads to incorrect directionality decisions.	[6], [14]
Negative sequence overcurrent elements	• The lack of negative sequence contribution by IBRs leads to a low level of supervising current, making the element not assert.	[15]
Pilot Protection	• Malfunctioning of the directional negative sequence overcurrent element causes incorrect permissive trip/block signals to the remote relay, leading to a wrong trip decision.	[3]
Line current differential (LCD)	• Changes in fault current patterns under IBRs cause LCD maloperation.	[16]
Rate-of-change-of-frequency (ROCOF)	• Large system ROCOF events leads to undesired tripping of embedded generation units.	[3]
Power swing protection	• Reduced inertia increases the rate of change of the swing impedance vector, which leads to a misinterpretation of the fast swings by the Power Swing Blocking (PSB). • IBRs may impact the impedance trajectory of the most severe stable swing, potentially causing the Out-of-Step-Tripping (OST) to misinterpret stable swing. • The dynamically changing source impedance changes the optimal location for the implementation of the OST.	[17], [18]

III. SIMULATION MODELS

Accurate simulation models that reflect the actual systems are designed to help engineers study and understand the behavior of a power system during abnormal conditions. Accurate simulation models help us better understand the effect of IBRs on the grid, their dynamic response, and protection requirements. Protection engineers use various simulation software for protection studies and fault analysis, such as ASPEN OneLiner and RTDS. To improve the performance of the line protection relay settings in the Dominion Energy network, a system with IBRs was modeled in two ASPEN OneLiner versions and RTDS. Fig. 3 illustrates the Single-Line Diagram (SLD) of the system that experienced an incorrect protection operation and described in Section II. The system comprises 13 buses, with two PV sites supplying the grid and some loads.

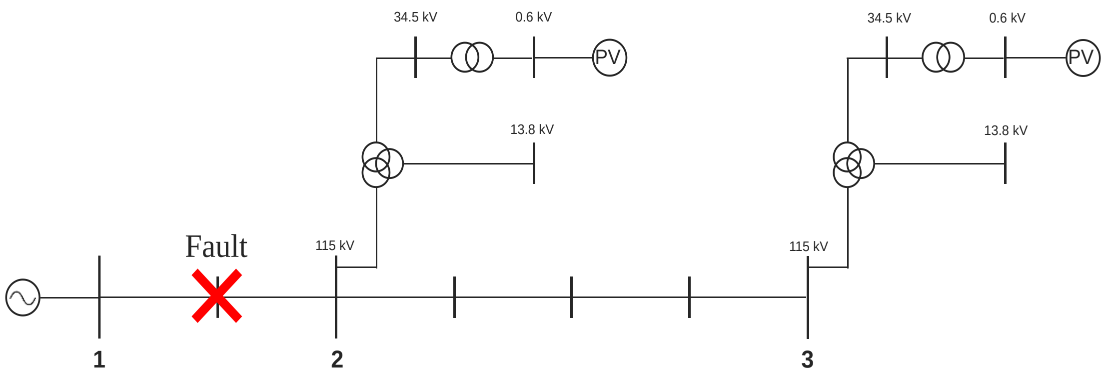


Fig. 3. SLD of a renewable based system in Dominion Energy network.

A. ASPEN Simulation

ASPEN OneLiner is a computer-based program used by protection engineers in the power industry for various tasks, including short-circuit analysis and relay coordination. One of the significant advantages of ASPEN OneLiner is its ability to speed up the process of developing protective relay settings for power systems. Engineers can make changes to relay settings and network configurations and quickly examine the effect those changes might have on the protection systems. This feature enables fast and accurate decision-making during power system planning, operation, and protection.

In earlier versions of ASPEN OneLiner, engineers had no choice but to model IBRs as SG, which is not an accurate model of their operation. However, with the new features of ASPEN OneLiner Version 15, IBRs can be modeled as converter-interfaced resources. Converter-interfaced resource model better represents the power electronic interconnection existing in the modern grid, and it has the capability to inject negative-sequence reactive current.

B. Real-Time Simulation

Real-time simulation is a computational technique that simulates dynamic systems and processes in real-time. It involves performing simulations at the same rate as real-world processes, allowing immediate and continuous feedback. It provides a realistic virtual environment to test and study the system response in different scenarios and enables the implementation of the hardware-in-the-loop setup, improving the simulation models' accuracy. The RTDS is a specialized hardware and software system used for real-time power system simulation. As seen in Fig. 4, the RTDS system consists of two main components:

- **Hardware:** The RTDS hardware is a custom-built, high-performance digital simulator that uses Field Programmable Gate Arrays (FPGAs) and Digital Signal Processors (DSPs) to perform real-time computations. These FPGAs and DSPs allow for extremely fast execution of power system models, making real-time simulation possible.
- **Software:** The RTDS software includes a user-friendly graphical interface that allows engineers and researchers to model and simulate power systems. Users can create detailed models of power system components such as generators, transmission lines, transformers, FACTS devices, PV sites, and loads.

The RTDS is an essential tool for researchers and engineers in the power industry to study and understand power system behavior in a controlled and safe environment. It has a crucial role in developing and testing new technologies and solutions for modern and renewable based power systems.

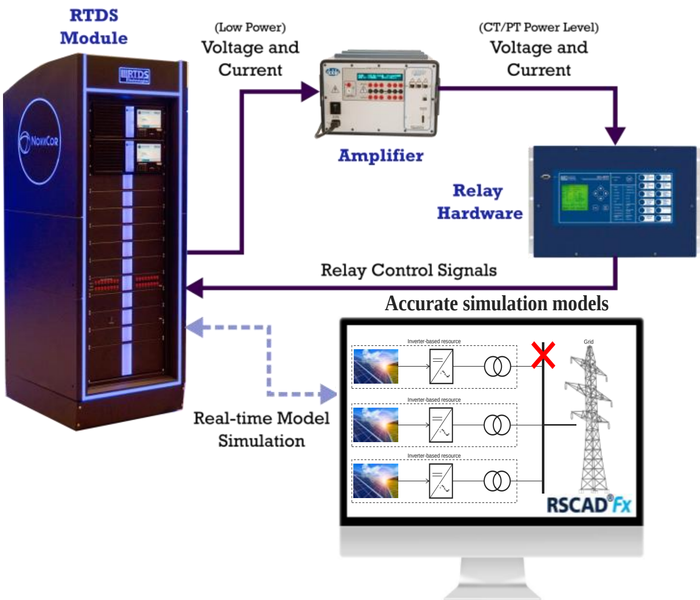


Fig. 4. RTDS main components.

IV. SIMULATION RESULTS

To help protection engineers choose the suitable fault analysis software and/or hardware, and to better understand the protection incident described in Section II, different fault types were applied to the system illustrated in Fig. 3. The same fault conditions are tested with the different ASPEN OneLiner models and RTDS models.

A. ASPEN Simulation Results

First, a single phase-to-ground fault was applied to the system to assess the effectiveness of the different ASPEN OneLiner versions and evaluate the simulation models' accuracy with a voltage-controlled current source and converter-interfaced resources. Based on the simulation results shown in Figs. 5 and 6, the fault currents in both ASPEN models are similar. The mean difference in the fault current quantities recorded in the different simulation models is around 3%. However, by applying a phase-to-phase-to-ground fault, some discrepancies were recognized in the positive sequence fault currents at buses two and three. Fig. 7 shows the difference between the ASPEN models and the actual records of the event. A 35% difference was documented between the old version of ASPEN simulation results and the actual record.

However, the mean difference between the new version of ASPEN and the actual records was 20%.

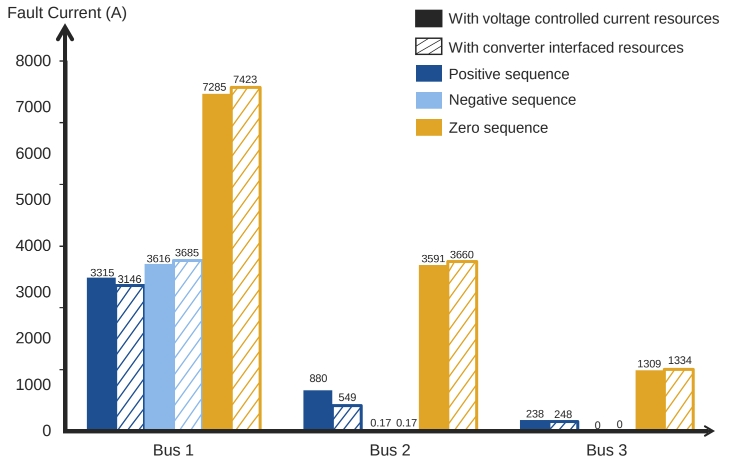


Fig. 5. Comparison between the fault sequence currents in the different versions of ASPEN OneLiner in the case of a single phase-to-ground fault.

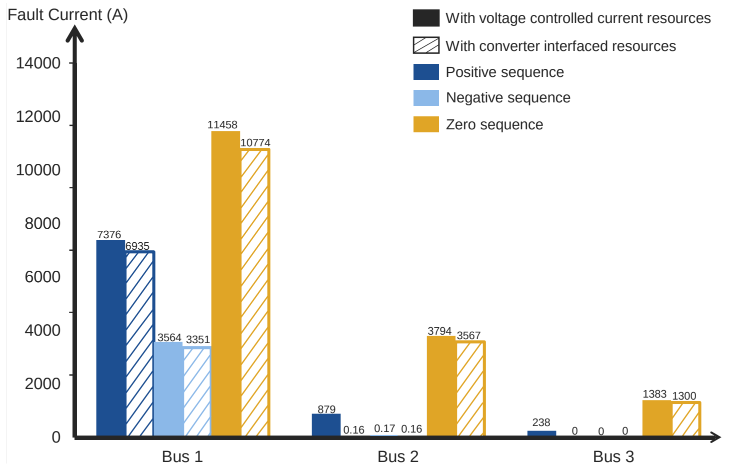


Fig. 6. Comparison between the fault sequence currents in the different versions of ASPEN OneLiner in the case of a phase-to-phase-to-ground fault.

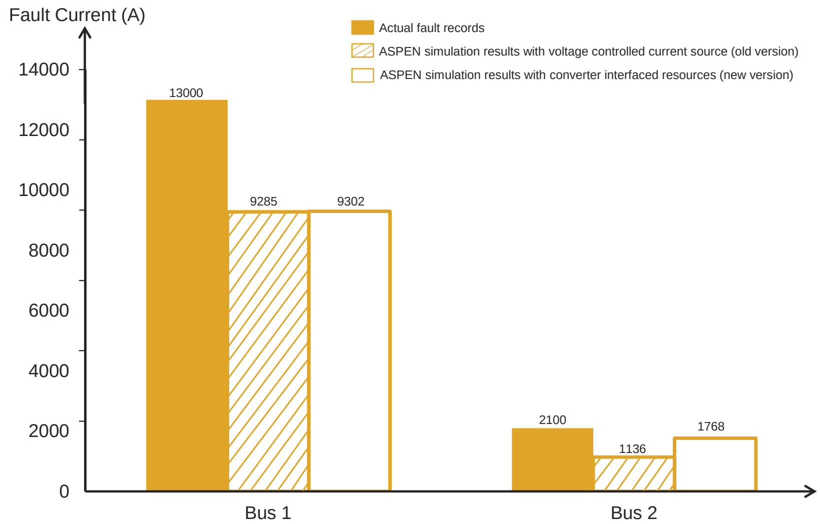
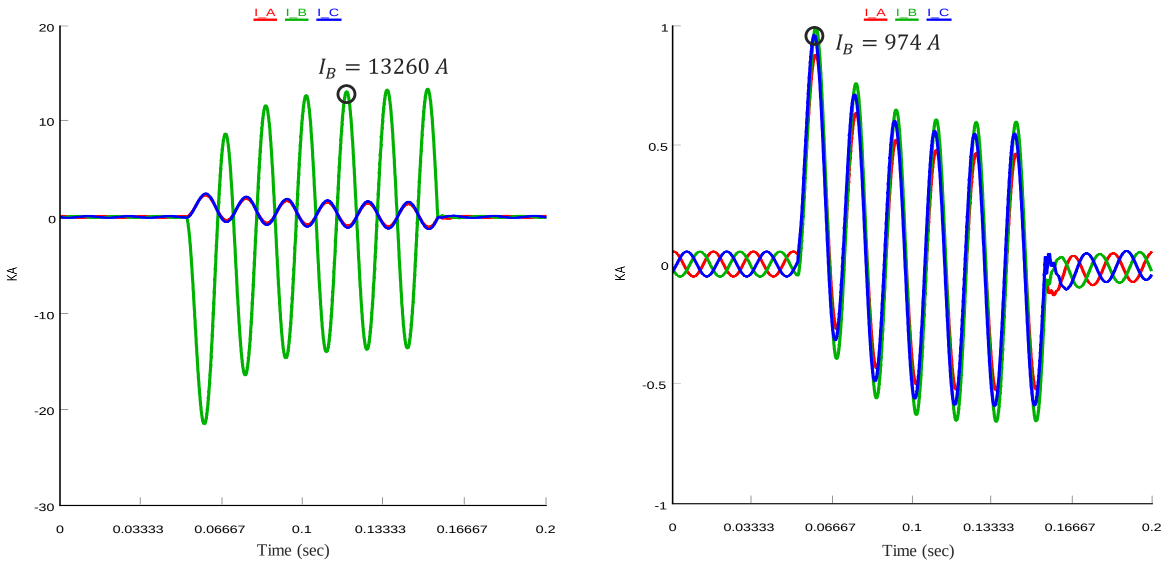


Fig. 7. Phase B fault current comparison between the actual fault records and ASPEN OneLiner simulations.

B. Real-Time Simulation Results

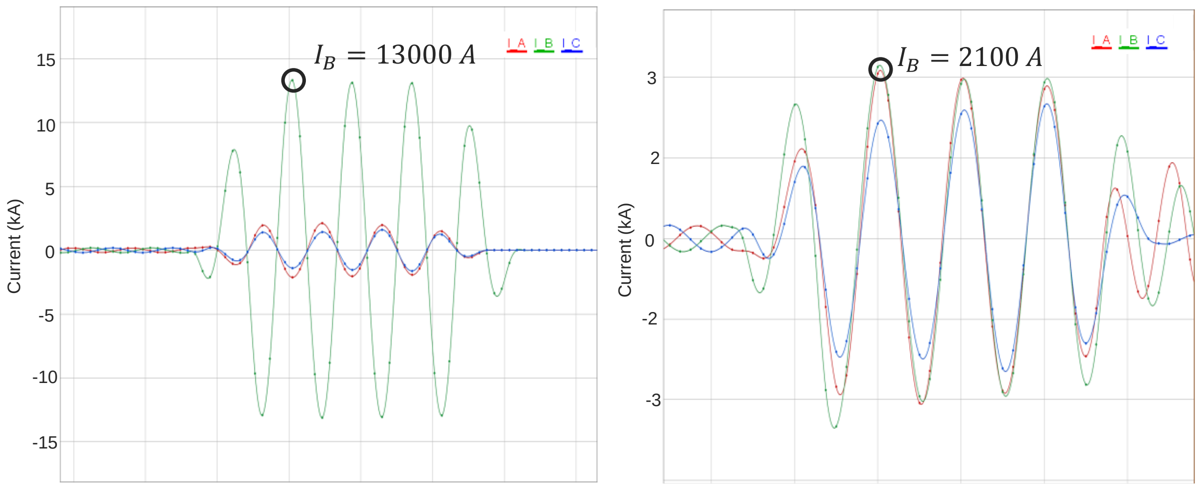
The single-phase-to-ground fault was simulated in real-time to assess the simulation model's accuracy. The mean difference between the real-time simulation results shown in Fig. 8 and the records of the phase fault currents illustrated in Fig. 9 is 3%.

Real-time simulation results showed high accuracy in representing the power system dynamics and fault incidents. Table II summarizes the simulation accuracy results attained in this study.



(a) Phase fault currents at bus 1 (b) Phase fault currents at bus 2

Fig. 8. RTDS phase fault currents.



(a) Phase fault currents at bus 1 (b) Phase fault currents at bus 2

Fig. 9. Event record of phase fault currents.

TABLE II
Summary of simulation model accuracy

Simulation model	**Mean difference between the event records and the simulation results**
Old version of ASPEN OneLiner (PV sites are modeled as SG)	20%
New version of ASPEN OneLiner (PV sites are modeled as converter-interfaced resources)	35%
RTDS	3%

V. CONCLUSION

The growing penetration of IBRs in the power grid is changing the grid dynamics and challenging the protection systems. This paper reviewed the main causes of protection challenges in renewable-based systems. Also, it described protection challenges associated with the interconnection of IBR facilities in the Dominion Energy network that could be useful for any company. To help protection engineers choose suitable fault analysis software, a renewable-based system in the Dominion Energy network was modeled in two versions of ASPEN OneLiner and in RTDS. The comparison between the real incident records and the different simulation results showed that the RTDS simulation had the highest simulation accuracy. When the two versions of ASPEN OneLinerTM were compared, version 15, where the solar PV sites were modeled as converter interface resources, can represent the system and the protection incident with higher accuracy.

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