RE-INTEGRATE EMT Simulation: Input Data Structures for Inverter-Based Systems

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***Abstract*— The increasing use of power electronics (PE) in generation, transmission, distribution, and loads has introduced the need for electromagnetic transient (EMT) simulation in power grids. Events in PE-based systems such as loss of load or partial trips during grid faults, are difficult to replicate without EMT simulations. EMT simulation for large systems containing PE-based systems requires properly structured model data. However, existing simulation software relies on proprietary data formats, and there is no standardized file format available for EMT simulation. This makes it challenging to develop, for example, detailed EMT simulation models of PE-based systems that are necessary to replicate events such as partial trips. In this paper, a data structure based on XML and DSS file formats is proposed for the EMT simulation of PE based systems connected to a distribution grid. The simulation is performed using the RE-INTEGRATE platform, where end-to-end automated parsing mechanisms are developed.**

***Index Terms*—EMT Simulation, distribution grid, inverters, converters, parser, XML, DSS, automation, power grid reliability, Common information model (CIM)**

I. Introduction

Power system operators face significant challenges in ensuring the reliability of the power grid due to the rapid integration of power electronics (PE)-based systems in generation, transmission, distribution, and loads. PE-based generation and loads exhibit different dynamics and characteristics compared to conventional generation and loads, such as limited overcurrent capacity and a lack of inherent inertia. Furthermore, the behavior of PE-based generation during extreme events—such as fires or hurricanes—can become unpredictable, often leading to occurrences such as partial trips.

The unexpected behavior of a PE-based data center, in [1], was observed when an asymmetrical fault in a transmission line caused disconnection of its 1500 MW load from the grid. Studies conducted under numerous disturbances reported by NERC (North American Electric Reliability Corporation) revealed that inverter-based generation unexpectedly tripped during normally cleared faults [2-5]. The trips were caused due to improper protection settings, the lack of proper models for PLL (Phase locked loop) loss of synchronism protection, inadequate fault ride-through support, and other factors [5]. These unpredictable behaviors of PE-based loads and generation cannot be accurately replicated in simulations that rely on aggregated or average models. To effectively reproduce such events, detailed (EMT) models are required [6, 7].

The share of PE-based loads, such as those in data centers, is rapidly growing. These PE-based loads present new challenges to the stable operation of the electrical grid, necessitating detailed EMT simulations. EMT simulation software typically utilizes proprietary file formats, and exchanging data between different software platforms requires careful data conversion. While the CIM is being adopted in some countries, mainly in Europe, for model exchange in power systems, it is not yet available for data exchange for EMT models [8-10]. There have been some efforts to define standardized data structures for EMT

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simulations [11, 12]. For instance, [12] proposes the use of the CIM for EMT. However, no standard model (such as CIM) for EMT has been finalized yet, that can store the detailed parameter needed for EMT simulation (such as PE converter's hardware and controller parameters).

In this paper, a novel input data structure for EMT simulations is presented using XML (Extensible Markup Language) and DSS file formats. The DSS file format is commonly utilized to store distribution grid parameters for steady-state and dynamic studies. However, DSS files do not include the parameters essential for EMT simulations. To address this limitation, an XML file is employed to include the parameters required for EMT simulation. The XML file encapsulates the parameters for power electronic (PE)-based generation and load.

The EMT simulation conducted in this study is implemented using the RE-INTEGRATE platform. This platform extracts simulation parameters by parsing the DSS and XML files, automates the construction of the distribution grid network, and executes EMT simulations. This will help with automated development of detailed models and assist with meeting transient ride-through requirements as well as to perform large-scale EMT simulations.

The paper is organized as follows: Section II discusses existing input data structures and the CIM architecture. Section III presents the proposed XML- and DSS-based file formats. The details of the DSS- and XML-based input data structures are explored in Section IV. The parsing architecture is described in Section V, while simulation results and the conclusion are presented in the subsequent sections.

II. Existing Input Data Structure and CIM Architecture

The data structure for EMT simulation models varies significantly across different software platforms, as each software employs its own proprietary data format. The exchange of model parameters between software platforms becomes a challenging and labor-intensive task due to the lack of compatibility among file formats. While the CIM provides a standard framework for power system model exchange, no such standard exists for exchanging model data specific to EMT simulations.

A. *Existing Data Structure*

Each software platform utilizes its own unique data structure for modeling. OpenDSS, commonly used for power flow simulations and dynamic studies, employs the DSS file format. format. However, DSS files lack the detailed parameters required for EMT simulations. PSS/E, another tool used for power flow and dynamic studies, utilizes the RAW and DYR file formats. The RAW file contains the parameters necessary to run steady-state simulations, such as power flow, while the DYR file includes data suited for dynamic studies. Meanwhile, PSCAD, dedicated to EMT simulations, uses a .pscx file structure. The use of different file formats across these software makes sharing parameters between tools a challenging and cumbersome process.

```
New Circuit.source phases=3 bus1=1 basekv=34.5 pu=1.00000 angle=0.00000 r0=0.00010 x0=0.00010 r1=0.010 x1=0.00010

New Linecode.mtx601 nphases=3 BaseFreq=60
~ rmatrix = (0.3465 | 0 0.3465 | 0 0 0.3465 )
~ xmatrix = (1.0179 | 0 1.0179 | 0 0 1.0179 )
~ units=mi

New Line.1    Phases=3 Bus1=1      Bus2=2    LineCode=mtx601 Length=500  units=ft

New Line.2    Phases=3 Bus1=2      Bus2=3    LineCode=mtx601 Length=300  units=ft
New Line.3    Phases=3 Bus1=3      Bus2=4    LineCode=mtx601 Length=200  units=ft

New Transformer.xfm1 phases=3 windings=2 xhl=2.720000 %imag=0.000 %noloadloss=0.000
~ normamps=22.90 emergamps=31.23
~ wdg=1 bus=4 conn=w kv=34.5 kva=150.0 %r=0.635000
~ wdg=2 bus=5 conn=w kv=0.48 kva=150.0 %r=0.635000

New PVSystem.3P_ExistingSite1a phases=3 bus1=5  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
New PVSystem.3P_ExistingSite1b phases=3 bus1=5  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
New PVSystem.3P_ExistingSite1c phases=3 bus1=5  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
New PVSystem.3P_ExistingSite1d phases=3 bus1=5  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
New PVSystem.3P_ExistingSite1e phases=3 bus1=5  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1

New Line.4    Phases=3 Bus1=3      Bus2=6    LineCode=mtx601 Length=300  units=ft
New Line.5    Phases=3 Bus1=6      Bus2=7    LineCode=mtx601 Length=200  units=ft

New Transformer.xfm2 phases=3 windings=2 xhl=2.720000 %imag=0.000 %noloadloss=0.000
~ normamps=22.90 emergamps=31.23
~ wdg=1 bus=7 conn=w kv=34.5 kva=150.0 %r=0.635000
~ wdg=2 bus=8 conn=w kv=0.48 kva=150.0 %r=0.635000

New PVSystem.3P_ExistingSite2a phases=3 bus1=8  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
New PVSystem.3P_ExistingSite2b phases=3 bus1=8  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
New PVSystem.3P_ExistingSite2c phases=3 bus1=8  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
New PVSystem.3P_ExistingSite2d phases=3 bus1=8  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
New PVSystem.3P_ExistingSite2e phases=3 bus1=8  kV=0.48 kVA=314 irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1
```

Fig. 1: Sample DSS parameter file

B. *CIM Architecture*

The CIM is a non-proprietary, open-source information model designed to facilitate the exchange of model data between different entities. CIM is based on the IEC standard and can be implemented in various file formats, such as XML or JSON. Originally introduced by the Electric Power Research Institute (EPRI) in the United States, CIM has gained greater adoption in Europe compared to North America for power system model exchange. A variant of CIM, known as the Common Grid Model Exchange Standard (CGMES), has also gained significant popularity in Europe, further establishing itself in power system applications.

III. XML and DSS Based Input Data Structure

In this paper, an XML and DSS-based input data structure is proposed to model PE-based generation and load. Fig.1 shows a sample DSS file containing a few parameters due to space constraints. The DSS file, which is used in the OpenDSS software, stores parameters of distribution grid components, such as transformers, pi-lines, and AC grid sources. Additionally, the DSS file contains some high-level information regarding PE converter-based generation and load (such as kV rating, kVA rating, irradiance, Pmpp, etc, as shown in Fig.1). However, a DSS file does not contain the detailed information about PE-based converters required for EMT simulations.

To address this limitation, detailed parameter information—such as controller parameters (e.g., controller gains, controller limits, current limits, etc.) and hardware parameters (e.g., filter parameters, types of filters)—is included in an XML file.

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```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<DCAC xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance">
        <DCACConverterGroup>
                <DCACConverter>
                        <DCAC_Hardware>
                                        <name>BusID</name>
                                        <value>1</value>
                                        <name>Inverter_type</name>
                                        <value>1</value>
                                        <name>RatedPower_MVA</name>
                                        <value>1</value>
                                        <name>RatedVoltage_kV</name>
                                        <value>480</value>
                                        <name>R1ac_Ohm</name>
                                        <value>1.0e-3</value>
                                        <name>L1ac_H</name>
                                        <value>3.0e-4</value>
                                        <name>IntegrationMethod</name>
                                         <value>2</value>
                        </DCAC_Hardware>
                        <DCAC_Controller>
                                        <name>Kp</name>
                                        <value>0.5</value>
                                        <name>Ti_s</name>
                                        <value>0.01992</value>
                                        <name>Pcon_mode</name>
                                        <value>1</value>
                                        <name>Pinv_ref_MW</name>
                                        <value>1</value>
                                        <name>QRef_MVA</name>
                                        <value>0</value>
                                        <name>Idmax_kA</name>
                                        <value>2</value>
                                        <name>Idmin_kA</name>
                                        <value>-2</value>
                        </DCAC_Controller>
                        <DC_source>
                                        <name>voc_kV</name>
                                        <value>1.0129</value>
                        </DC_source>
                </DCACConverter>
        </DCACConverterGroup>
</DCAC>
```


Fig. 2: Sample XML parameter file (with a few parameters)

Fig.2 shows a sample XML parameter file that contains a few parameters. The XML file follows a hierarchical structure, where a dc-ac converter is grouped under the dc-ac converter category. The dc-ac converter is further subdivided into dc-ac hardware, dc-ac controller, and dc source.

The dc-ac hardware parameters include bus data to be used for connecting the converter to the desired bus, the type of converter, the type of filter, filter parameters, etc. The controller parameters include controller gains, limits on the controller output, current limits, control modes, reference parameters, etc. Depending on the selected control mode, some parameters become mandatory, while others are optional. The dc source, which could be any generation source or modeled as a load, contains parameters associated with the characteristics of the generation or load.

IV. Parsing and Automation

A. Parsing Architectures

The PE based generation plant model is constructed by parsing data from both a DSS file and an XML file. The DSS file provides parameters and bus connectivity information for each component in the distribution system, whereas the XML file contains additional parameters that are not available in the DSS file, specifically for the converters. If the DSS parser detects any converter in the DSS file, it directs the XML parser to look for additional parameters from an XML file. The parameters in the XML file include both software parameters (e.g., control gains, PLL parameters, switching frequency, etc.) and hardware parameters (e.g., ac filter parameters, dc capacitance, etc.).

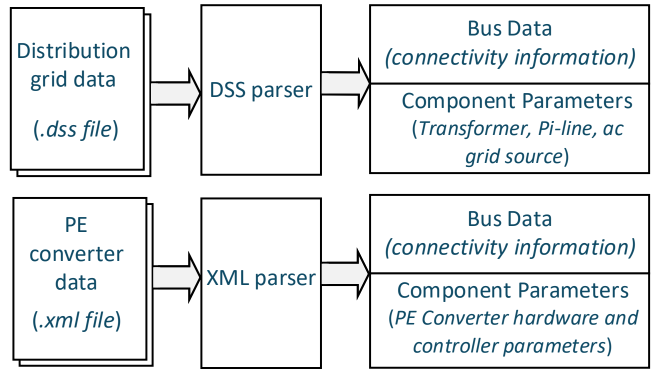

Fig. 3: Parsing architecture block diagram

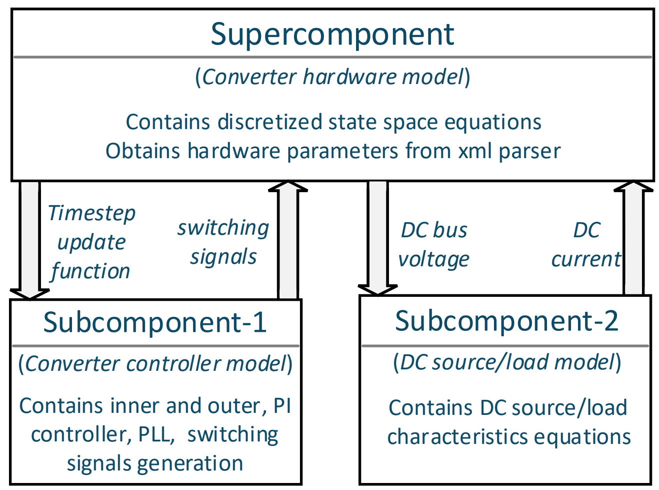

Fig. 4: Component model of the PE converter

Fig. 3 illustrates the block diagram of the proposed parsing architecture. The DSS parser extracts data from the DSS file and stores it as bus data and component parameters. The bus data includes the connectivity information for each component, which is subsequently used by automation to establish electrical connections. Similarly, the XML parser retrieves both bus data and component parameters for PE converters but organizes the component parameters into super-components and sub-components of the PE converter.

B. Component Model

The component model includes discretized differential-algebraic equations (DAEs) for individual components (A_{comp} and B_{comp}). Within the component model of PE-based converter, a super-component and sub-component structure is defined as shown in Fig. 4. The component which has sub-components is described in the super-component like the converter hardware. The sub-components in this case include converter controller and dc source/load, which are linked to the super-component. The hierarchical information contained in the XML file is mapped and passed directly to the corresponding super-component and sub-components of the converter model.

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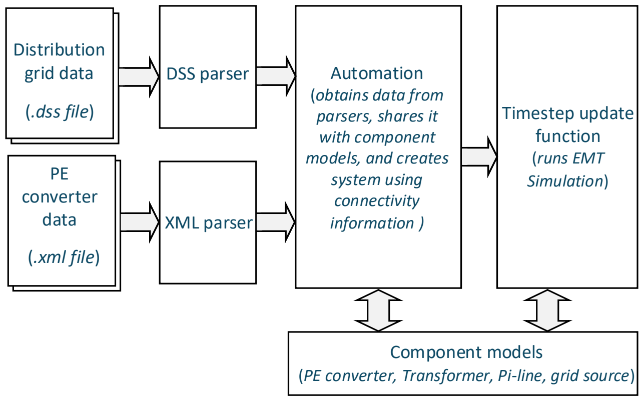

Fig. 5: Parsing and automation block diagram for EMT simulation

C. Automation for EMT Simulation

The automation process utilizes the parsed parameter information obtained from the DSS and XML parsers, as shown in Fig. 5. This parsed information includes bus data, which the automation system uses to establish electrical connectivity for the model. Additionally, the automation system transfers component parameter information from the parsers to the component model. The timestep function updates the system equations (discretized DAEs), that are subsequently solved by the solver to obtain the states at each time step.

The PE-based plant for generation or load, as illustrated in Fig. 6, has been modeled for EMT simulations using a parser and an automation framework, successfully yielding EMT simulation results. The PE based load generally has uninterrupted power supply (UPS) in their architecture, but, for our simulation, the individual loads are fed by two-level converters based active rectifiers.

The (PE)-based plant connected to a distribution grid which can be modeled either as generation units or as loads. In the case of a generation plant, each individual converter behaves as an inverter, supplying power from the DC source to the grid. And, in the case of a load plant, the individual converters act as active rectifiers. The model comprises five feeders, with each feeder containing multiple π-lines and five transformers. Each transformer is connected to five inverters/rectifiers, resulting in a total of 125 inverters/rectifiers in the plant. Each inverter/rectifier is modeled as a detailed switching model to enable accurate EMT simulations.

The DSS parser extracts distribution grid parameters and connectivity information from the DSS file, while the XML parser retrieves detailed converter parameters from the XML file. The automation process then utilizes the parsed information to build the network and execute the EMT simulation.

V. Simulation Results

The plant model discussed in the previous section (Fig. 6), is simulated on the RE-INTEGRATE EMT simulation platform, when it acts as a generation plant and as a load plant. The simulation results for the PE-based generation plant model, depicted in Fig. 7, illustrate the grid voltage and the total grid current at the collector bus. The simulation results show a reduction in collector current as the power reference is reduced at t = 0.03 s. The total grid current represents the sum of currents generated by all individual inverters within the plant.

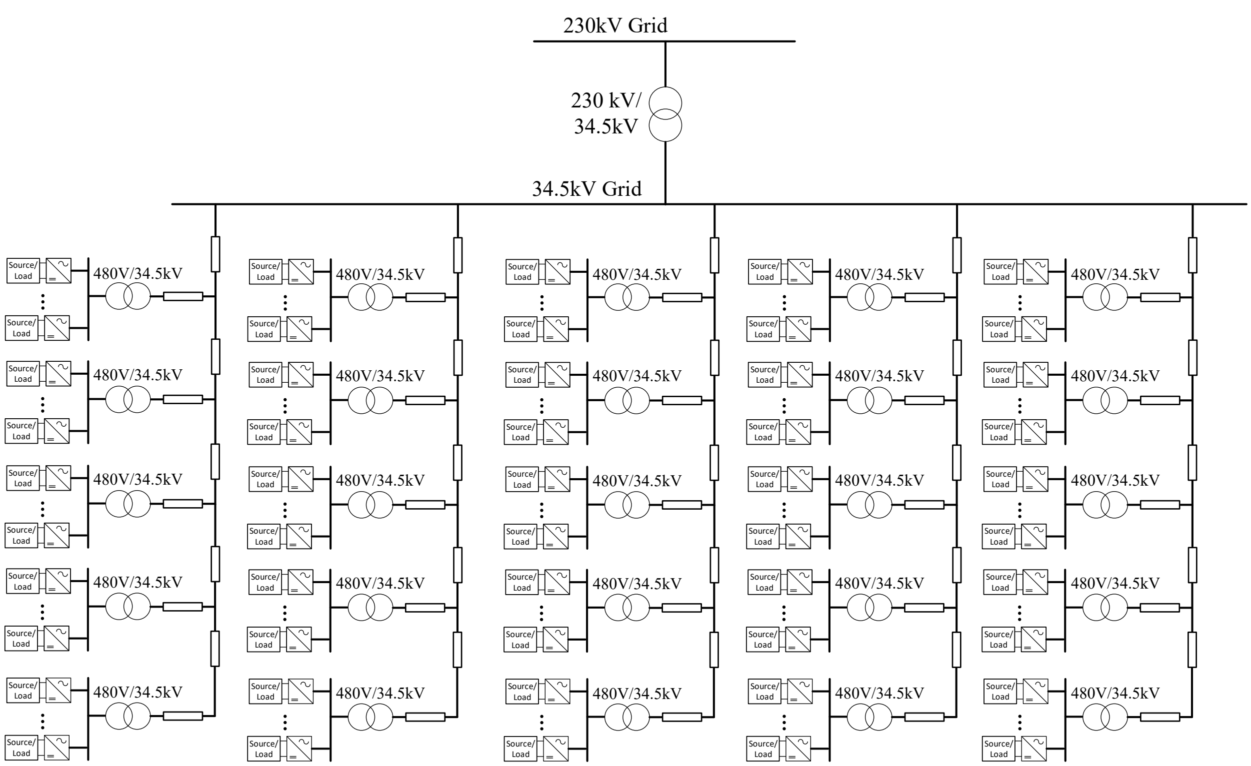

Fig. 6: PE based generation or load plant connected to distribution grid

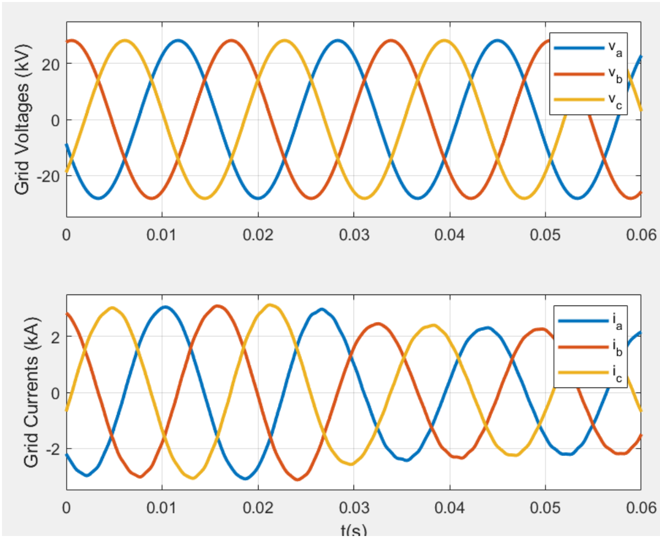

Fig. 7: Grid voltage and current of the PE based generation at collector bus

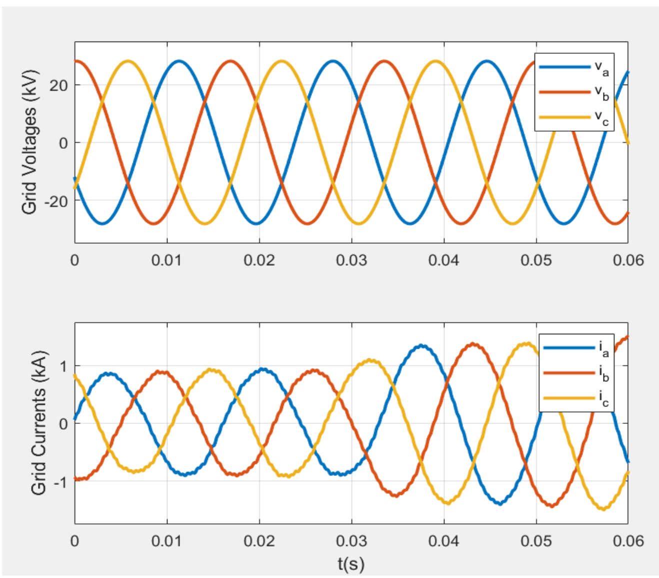

Fig. 8: Grid voltage and current of the PE based load at collector bus

Similarly, the plant can be modeled as a load plant where each converter is behaving as an active rectifier. The results for the PE-based load plant model, shown in Fig. 8, illustrate the grid voltage and the total grid current at the collector bus. The total grid current represents the currents drawn by all individual active rectifiers within the plant. The simulation results show an increase in collector current as the power reference is increased at t = 0.03 s.

These simulation results indicate the stability of the process and it is shown to be accurate and as expected based on the commands provided.

VI. Conclusion

The paper introduces an input data structure utilizing XML and DSS file formats to facilitate EMT simulations for PE-based generation and loads. It highlights the absence of a standardized file format for EMT simulation model parameters and briefly discusses the CIM architecture designed for exchanging power system models. Furthermore, the paper emphasizes the need for a similar framework to exchange EMT simulation model parameters.Converter parameters and distribution grid parameters are stored in XML and DSS files, while the parsing and automation process required to execute EMT simulations is illustrated using block diagrams. The obtained data structures help in setting up automated development of detailed models of PE-based systems that are needed to evaluate partial trips in the system. In addition, the simulation results obtained from the RE-INTEGRATE platform for PE-based generation and loads are presented and showcase the success in using the proposed data structures.

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