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High Penetration Power Electronics Grid: Modeling and Simulation Gap Analysis

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Transformer Resilience and Advanced Components (TRAC) Program

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ACRONYMS

AEMO	Australian Energy Market Operator
ATP	Alternative Transient Program
AVR	automatic voltage regulator
CAISO	California Independent System Operator
CMPLDW	composite load model
DER	distributed energy resources
EI	Eastern Interconnection
EMS	energy management system
EMT	electromagnetic transient
EMTP	ElectroMagnetic Transient Program
ERCOT	Electric Reliability Council of Texas
ETAP	Electrical Transient and Analysis Program
FACTS	flexible alternating current transmission systems
FPGA	field programmable gated array
GPU	graphic processing unit
HIL	hardware-in-the-loop
HMI	human machine interface
HVdc	high-voltage direct current
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent System Operator
MISO	Midcontinent ISO
MTdc	multiterminal direct current
NE-ISO	New England Independent System Operator
NERC	North American Electric Reliability Corporation
OpenDSS	Open Distribution System Simulator
ORNL	Oak Ridge National Laboratory
PE	power electronics
PF	power flow
PHIL	power hardware-in-the-loop
PNNL	Pacific Northwest National Laboratory
PSCAD	Power System Computer Aided Design
PSLF	Positive Sequence Load Flow
PSS®E	Power System Simulator for Engineering
PV	photovoltaic
QSTS	quasistatic time series
RSCAD®	real-time digital Simulator Computer Aided Design
SCR	short circuit ratio
SPP	Southwest Power Pool
SPS	SimPowerSystems
SSPS	solid-state power substation
SSSC	static synchronous series compensators
STATCOM	stationary compensator
T&D	transmission and distribution
TS	transient stability
VSC	voltage-source converter
WECC	Western Electricity Coordinating Council
WI	Western Interconnection

EXECUTIVE SUMMARY

Increased penetration of power electronics in the grid is happening through development of high-power drives (like in Type 3 or 4 wind turbines, industrial drives, etc.), high-voltage direct current (HVdc) systems, flexible alternating current transmission systems (FACTS), energy storage systems (ESSs), inverter-based renewables like solar and wind, electric vehicle chargers, and other technologies. Ongoing research and development in new power electronic technologies including, but not limited to, solid-state power substations (SSPS), extreme fast charging (XFC), solid-state transformers, and multi-port power electronics that integrate multiple sources/loads will further increase penetration levels. To ensure stakeholders can integrate high penetration of power electronic technologies safely and reliably requires tools and methods to assess and evaluate their impact on the grid.

Objectives: This report surveys, assesses, and analyzes commercially available and open-source tools that can support the assessment and evaluation of power electronics in future grids with high penetration levels. The study includes aspects that range from power flow analysis to dynamics evaluation (including hardware-in-the-loop – HIL testing) for such systems. The challenges and gaps associated with the current generation of toolsets available to assess the technical impact of introducing high penetration of power electronics are reported. The method is summarized in Figure ES-1.

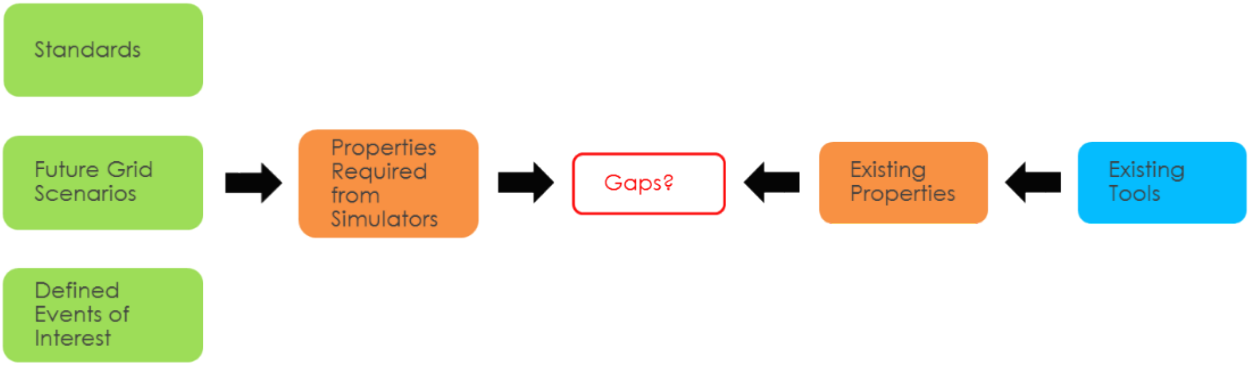


Figure ES-1. Methodology to identify gaps in existing tools to simulate high penetration of power electronics in grid.

Value Proposition: The contents of this report can enable decision makers and investors to make informed decisions about future investments in improving simulation tools. This work quantifies the gaps in assessing future grids and the corresponding improvements required in future simulation tools.

1. INTRODUCTION

1.1 ANALYSIS TOOLS

To study the characteristics of the grid or a component in the grid and its operations, models of the corresponding characteristics need to be developed. These models are then processed and simulated by a tool to generate the characteristics of the grid or the component in the grid and its operations. The tools available to study the grid or a component in the grid in an offline simulation have been characterized based on the time step used to simulate the model. The tools include component/electromagnetic transient (EMT) simulators, electromechanical transients or transient stability (TS) simulators, quasi-static time series (QSTS) simulators, and power flow (PF) or short circuit simulators. Some of the studies performed using these tools and the corresponding time steps used are shown in Figure ES-2.

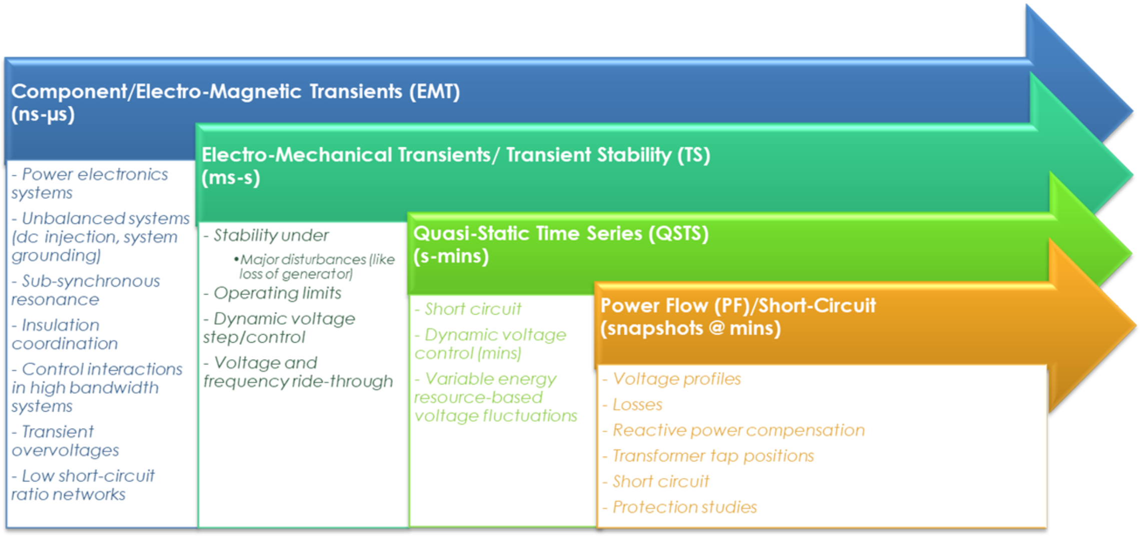


Figure ES-2. Analysis tool characterization and some of the studies performed using the tools.

The model simulated in a tool is developed by the user and represents the characteristics of the system being analyzed. For example, in an EMT simulation of the dynamics of the power grid, the user identifies the individual components of the power grid from the model library and designates their connections. The user can also develop custom models representing the EMT dynamics of individual components. Ultimately, models represent the EMT dynamics of individual components in the form of differential algebraic equations (DAEs) or algebraic equations. Once the model is generated, the EMT simulator processes the model (i.e., the DAEs) by discretizing and linearizing the model, and solving the resultant linear system of equations at every time step. A similar process is followed in other simulators.

Corresponding software and hardware perform real-time simulation of component/EMT models, TS models, and QSTS models. Some of these software and hardware have been used to perform hardware-in-the-loop (HIL) simulations.

1.2 PENETRATION DEFINITION

To begin the discussion on high penetration of power electronics, one of the critical factors is the definition of the term "penetration of power electronics." In this report, the penetration of power electronics is not limited to the integration of variable renewables resources, but it also includes the power electronics that are expected to be present in variable-speed drives connecting to traditional synchronous generators, power flow controllers, energy storage devices, loads, and other forthcoming power electronic technologies (e.g., solid-state power substations). "Penetration of power electronics" can be defined as the weighted average of power passing through power electronics in the grid. This definition provides an indication of the number of power electronics equipment present in the grid, the rating of the power electronics equipment, and the proximity of power electronics from each other. Although the number and rating of power electronics are inherently identified in the weighted average, their proximity can be identified by calculating the penetration of power electronics in local regions separately. The weighted average is the ratio of the summation of the power passing through power electronics at each bus to the summation of generation, load, and branch power that is weighted by the presence of power electronics. In this formulation, the power terms are absolute values and are considered greater than zero. A simple system is shown in Figure ES-3.

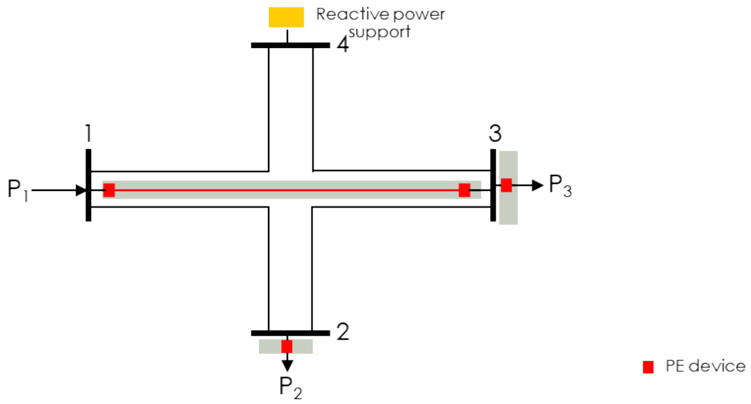


Figure ES-3. Simple ac grid network with power electronics.

The corresponding penetration of power electronics is given by

$$P_{\%}^{PE} = \frac{\text{Summation of power flowing through power electronics at each bus}}{\text{Summation of generation, load, and branch powers (weighted for PE buses)}}$$

$$= \frac{\overbrace{(P_{13})}^{\text{Bus-1}} + \overbrace{(P_2)}^{\text{Bus-2}} + \overbrace{(P_{13} + P_3)}^{\text{Bus-3}}}{(P_1) + (P_2 + P_3) + (2P_{13} + P_{14} + P_{12} + P_{23} + P_{34})} \quad .$$

An approximation of the formula is provided below:

$$P_{\%}^{PE} = \lambda_g \frac{\text{Generation PE}}{\text{Total generation}} + \lambda_l \frac{\text{Load PE}}{\text{Total load}} + \lambda_{pfc} \frac{\text{PFC PE weighed power}}{\text{Total weighted power through branches}}$$

$$= \lambda_g \frac{0}{P_1} + \lambda_l \frac{(P_2+P_3)}{(P_2+P_3)} + \lambda_{pfc} \frac{(2P_{13})}{(2P_{13}+P_{14}+P_{12}+P_{23}+P_{34})}$$

This formula is a valid approximation if the total generation, total load, and total weighted power through branches are similar. This is, in general, a valid argument in the power grid. “Penetration of power electronics” can also be defined as the weighted average of power electronics in generation, load, and power flow controllers. This definition is simpler to calculate for transmission planners, planning coordinators, reliability coordinators, generator owners, and generator operators, among others.

In this report, future scenarios are evaluated for 0–20%, 20–50%, and 50–100% penetration of power electronics in the grid. The corresponding scenarios are designated as *traditional*, *intermediate*, and *long-term* scenarios. These classifications are based on the penetration of power electronics expected in the grid in the near-term (2–5 years), mid-term (5–10 years), and long–term (>10 years), respectively. Penetration percentages are based on projections for the amount of renewables integration in the grid, power electronics in loads, and power flow controllers introduced. The penetrations are defined based on the formulae above using rated power capacities. The definition can be extended to grid operations, where the instantaneous penetration of power electronics can be calculated based on operating power conditions (rather than rated power of components).

1.3 LITERATURE OVERVIEW OF STUDYING HIGH PENETRATION POWER ELECTRONICS IN GRIDS

Several workshops have been conducted in United States and Europe on the future grids with high penetration of power electronics [1, 2, 3, 4]. In these workshops, an explicit definition of *power electronics penetration* was not provided, and discussion primarily focused on the integration of renewable resources. The challenges presented in these workshops are included in the literature reviewed below.

1.3.1 Dynamic Simulations (Component/EMT/TS)

In this section, some of the studies performed in the past 5 years on grids with increased penetration of power electronics using dynamic simulations are discussed. The challenges involved in grid with high penetration of power electronics and in performing such studies are briefly surveyed.

Several independent system operators (ISOs) in United States are performing or have performed stability analysis on grids with high penetration of power electronics-based resources. Similar studies have been performed by utilities or grid operators worldwide. The studies that used TS simulation tools are first discussed in this section. One of the studies performed by Midcontinent ISO (MISO) on high penetration of renewables in low loading scenarios identified instability in the grid upon loss of generation. This study indicated stability may be improved by using HVdc links to transport renewables, which is less expensive compared to the traditional upgrades needed in the alternating current (ac) grid [5]. A study performed by Southwest Power Pool (SPP) assessed stability limitations with increased penetration of wind power plants [6]. Short circuit ratio (SCR) analysis has also been performed in the study to identify strengths at the locations of integrating generation resources. This study identified critical clearing times and SCRs in different regions to understand the stability limitations. Based on the simulations in the study, a few unstable operating conditions have been identified, and advanced control methods were recommended for the inverter-based generations. A study performed at California Independent System Operator (CAISO) [7] demonstrated improved transient voltage performance from inverter-based generation through improved damping and faster voltage recovery. Concerns have been raised in the study for high penetration of inverters without ride through capabilities that limit recovery upon events. Another observation is the prevalence of high voltages with large penetration of distributed solar generation. The influence of increased penetration of wind and solar in Western Interconnection (WI) has been studied in [8, 9]. These studies have identified the requirements for fast frequency response and transmission upgrades that may assist in TS of the WI. Similar studies have also been considered with high penetration of solar in Eastern Interconnection (EI) [10, 11] and of wind in EI [12]. These studies identified the inter-area oscillations in the interconnection, damping requirements in the interconnection, and fast frequency support (through inertial and governor control) needed in the interconnection. The frequency response trends in the three US interconnections of EI, WI, and Texas Interconnection has been studied with increased penetration of solar energy [13]. Several studies have been performed on the grid in Europe with increased penetration of power electronics. For example, a study was performed on the grid in Ireland to identify the challenges introduced in protection systems at higher penetration of renewables with increased rate of change of frequency [14]. Other examples were included in the MIGRATE [1] and RESERVE projects [2], which study various challenges with a power electronics–dominated grid in Europe. These studies used TS and EMT simulation tools. In addition to the study of increased penetration of renewables, studies were also performed on HVdc systems [15, 16, 17], to name a few. The studies are summarized in Table ES-1.

Table ES-1. Summary of studies on US grids with high penetration of power electronics that used TS simulation tools.

Organization/ Reference	Scenarios and Studies	Challenges Identified	Improvements/Recommendations
MISO [5]	High penetration of renewables in low loading scenarios.	Instability in the grid upon loss of generation.	Stability maybe improved by using HVdc links to transport renewables.
SPP [6]	To assess stability limitations with increased penetration of wind power plants. SCR analysis to identify strengths at the locations of integrating generation resources.	Identified critical clearing times and SCRs in different regions causing a few unstable operating conditions.	Advanced control methods were recommended for the inverter-based generations.
CAISO [7]	Inverter-based generation through improved damping and faster voltage recovery.	Concerns for high penetration of inverters without ride through capabilities that limit recovery upon events were raised. Prevalence of high voltages with increased penetration of distributed solar generation.	Improved transient voltage performance was indicated.
WI study in [8, 9]	Impact of increased penetration of wind and solar.	TS challenges being resolved.	Identified the requirements for fast frequency response and transmission upgrades that may assist in TS of the WI.
EI study in [10, 11, 12]	Impact of increased penetration of wind and solar.	Identified the inter-area oscillations in the interconnection.	Identified damping requirements in the interconnection, fast frequency support (through inertial and governor control) needed in the interconnection.

There has been an increasing trend toward using EMT simulation tools to perform stability studies on larger areas of the grid with increased penetration of renewables. For example, the North American Electric Reliability Corporation (NERC) and the Western Electricity Coordinating Council (WECC) study on the fault response of the photovoltaic (PV) plants or distributed energy resources (DERs) in California during fire incidents [18, 19, 20] have identified the need for higher fidelity models of PV and wind plants and the grid. The challenge with the existing models and simulation methods is the inability to replicate the behavior of PV and wind plants upon unbalanced faults that affect the reliability of the grid. The study also indicated the increasing need for EMT simulations. EMT simulations of PV plants and grids has been performed in one of the studies by Sandia National Laboratories to assess and identify the influence of negative-sequence injections during unbalanced faults on the protection relays [21]. These studies also discuss the stability challenges in a weak grid with inverter-based resources and different SCR metrics suitable in such conditions. Studies on EMT simulation of (i) PV plants and grids during faults [22, 23] and (ii) DERs interactions with bulk power system by New England Independent System Operator (NE-ISO) [24] are ongoing. The NE-ISO study is researching the stability with increased penetration of DERs in low load regions due to interactions between controllers, weak grids, trip during grid events, among others. The projects in [22, 23] are exploring advanced modeling of PV plants and grid simulation methods that can aid in studying the stability and reliability of higher penetration of PV plants or DERs in the grid.

An EMT simulation of the grid in the Texas Pan Handle region with high penetration of wind resources was performed by Electric Reliability Council of Texas (ERCOT). The goal of the study was to assess the effect on stability of the grid with increased penetration of power electronics (PE)-based generation [25]. A similar study was also performed by Australian Energy Market Operator (AEMO) for the increased penetration of wind in Southern Australia [26]. The ERCOT and AEMO studies were performed to identify the stability of the grid and the protection related challenges with increased penetration of wind. EMT simulations were used in these studies to understand subsynchronous control interactions that are not observed in the traditional models. Also, they have been used to identify the minimum non-power electronics generation using synchronous machines needed to maintain stability of the grid. Finally, they have identified the need to develop SCR metrics to quantify the strength of the grid with high penetration of inverter-based resources. The EMT simulation of wind power plants in a small region of 130 buses and 7 wind power plants was also performed by SPP [6]. The study considered a local region that is characterized by low critical clearing time and SCR. The study's results showed a close correlation between the control system in wind power plants and the stability of the region's grid. Other EMT studies are being performed to study control interactions in wind power plants [27].

Several other EMT simulation studies have been performed for other power electronics driven resources. One of the studies considers the benefits of introducing a higher penetration of solid-state power substations like HVdc systems. An Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) [28, 29] study considered different configurations of HVdc systems based on voltage-source converters (VSCs) and line-commuted converters (LCCs) connecting US interconnections. One configuration is a VSC based multiterminal direct current (MTdc) systems connecting EI, ERCOT, and Western Interconnection (WI) grids. The VSC-based MTdc system can use higher bandwidth control systems compared to the traditional LCC-based HVdc systems. EMT simulations were used in this study to research the advanced high-bandwidth control methods that may be introduced in the VSCs and MTdc systems to provide fast frequency response sharing across interconnections and dynamic voltage support locally. The traditional TS simulations are inadequate to identify the stability of high-bandwidth control methods because of the inadequate fidelity in the models. Hybrid EMT-TS simulations were also explored in the study. Other EMT simulation studies were performed by ORNL to study the impact of dynamic wireless charging and the corresponding solid-state power substation (SSPS) requirements in the grid [30], benefits of multiport power electronics integrating several resources (like PV, energy storage) to the grid [31], challenges associated with extreme fast charging and DERs, and microgrids [32]. Several other literature studies have considered EMT simulations to study increased penetration of power electronics in grids [33, 34]. EMT simulation studies are summarized in Table ES-2.

Table ES-2. Summary of studies on US grids with high penetration of power electronics that used EMT simulation tools.

Organization/Reference	Scenarios and Studies	Challenges Identified	Outcomes
NERC and WECC [18, 19, 20]	Fault response of the PV plants or DERs in California during the fire incidents.	Challenge in the existing models and simulation methods is the inability to replicate the behavior of PV and wind plants upon unbalanced faults.	Identified the need for higher fidelity models of PV and wind plants and grid. Also indicated the increasing need for using EMT simulations.
Sandia National Laboratories [21]	The impact of negative-sequence injections during unbalanced faults on the protection relays.	The stability challenges in a weak grid with inverter-based resources.	Different SCR metrics that are suitable to evaluate these conditions.
Study in [22, 23]	Study of PV plants and grids during faults.	Stability and reliability of high penetration of PV plants or DERs in grid.	Ongoing studies that are expected to develop advanced models of PV plants and grid simulation methods using existing tools.
NE-ISO [24]	DERs interactions with bulk power system.	Researching the stability with increased penetration of DERs in low load regions due to interactions between controllers, weak grids, trip during grid events, among others.	Ongoing study.
ERCOT [25] and AEMO [26]	Assess the impact on stability of the grid with increased penetration of power electronics-based wind generation in the Pan Handle region (ERCOT study). Increased penetration of wind in Southern Australia (AEMO study).	Stability of the grid and the protection related challenges with increased penetration of wind.	EMT simulations have been used to understand subsynchronous control interactions that are not observed in the traditional models. Identified the minimum non-power electronics generation using synchronous machines needed to maintain stability of the grid. Identified the need to develop SCR metrics to quantify the strength of the grid with high penetration of inverter-based resources.
SPP [6]	Simulation of wind power plants in a small region of 130 buses and 7 wind power plants was performed.	Stability of the local region with high penetration of wind.	A close correlation between the control system in wind power plants and the stability of the region's grid was observed.

Table ES-2. Summary of studies on US grids with high penetration of power electronics that used EMT simulation tools (continued).

Organization/Reference	Scenarios and Studies	Challenges Identified	Outcomes
ORNL, PNNL [28, 29]	Different configurations of HVdc systems based on VSCs and LCCs connecting US interconnections have been researched.	Traditional TS simulations are inadequate to identify the stability of high-bandwidth control methods due to the inadequate fidelity in the models.	EMT simulations have been used to research the advanced high-bandwidth control methods that may be introduced in the VSCs and MTdc systems to provide fast frequency response sharing across interconnections and dynamic voltage support locally. Hybrid EMT-TS simulations have also been explored in the study.

TS simulation tools may not provide accurate representation of the dynamics of grids with increased penetration of power electronics [25]. The challenges in simulating accurately the grids with increased penetration of power electronics using TS simulation tools arise from low SCR, high bandwidth control systems, control interactions, and sensitivity of power electronics to external disturbances, to name a few. Challenges in simulating grids with TS simulation tools lead to the increased use of EMT simulation tools. One of the concerns raised by the aforementioned studies include the increased computation burden imposed by EMT simulations and the ability to collect data to develop high-fidelity models. For example, the time taken to simulate the EMT simulation models of the South Australian grid in an AEMO study for a 20 s duration of simulation is 3 h. Similarly, the time taken to simulate the EMT simulation models of the Texas Pan Handle region in ERCOT study for a 30 s duration of simulation is 2 h.

1.3.2 Steady-State Simulations (QSTS/PF)

Studies performed on grids with increased penetration of power electronics using steady-state simulations during the past 5 years are discussed in this section. The challenges involved in grids with high penetration of power electronics and in performing such studies are briefly surveyed.

Power flow algorithms with increasing portion of dc networks have not been fully developed nor widely adopted by industry. Current algorithms iterate between solutions of the ac and dc systems [35]. This method provides sufficient accuracy in analyzing current grids with few dc portions in the system.

Additionally, power flow models and data sets should capture static reactive capability of wind and solar renewable generation [36]. Currently WECC modeling working groups are creating data sets and testing models to capture high penetration of DER [37]; power flow model structure and explicit representation of DER are being considered.

A recent trend also considers cosimulations between transmission and distribution (T&D) models [38]. To achieve higher accuracy, the cosimulation involves iterations between solutions in the transmission model and the distribution models. Since there is increasing penetration of DER and the distribution networks could become much dynamically active in the future, large scale T&D cosimulations will be needed, which would require improvement in simulation methods and algorithms.

NERC [39] currently requires transmission operators and reliability coordinators to perform a contingency analysis every 30 min using real-time information. The contingency analysis is currently based on power flow solutions, which means that transmission operators and reliability coordination need to solve algorithms and analyze results of many contingencies within a short time. The requirements are further exacerbated with increased penetration of power electronics that may require T&D power flow simulations or ac-dc power flow simulations.

Some of the QSTS simulation experiences to study high penetration of power electronics–based solar generation is presented below. Most of the QSTS modeling efforts have been concentrated at the distribution level [40] to study behavior of distribution feeders for high penetration of solar distributed generation, as well as for studying the effect of demand–response programs with multistate load models [41]. In addition to the QSTS studies for distribution, there has been a trend of applying QSTS toward studying larger geographic areas, beyond distribution, to include subtransmission. There have also been efforts to develop HIL QSTS and adaptive simulations. With the increase in renewable variable generation in larger geographic areas, these initial trends may become a required modeling practice. PNNL collaborated with Duke Energy to identify the need for QSTS at subtransmission level to evaluate the impact of new power flow patterns propagating from distribution to subtransmission as solar photovoltaic generation increases [42]. As part of a follow up effort, PNNL developed a new subtransmission and distribution cosimulation tool and control strategy called the Coordinated Real-Time Sub-Transmission Volt–Var Control Tool (CReST-VCT). CReST-VCT was tested on a Duke Energy Carolina system to demonstrate the effect of the voltage control capability by dispatching DERs' reactive power support [43]. The algorithm runs every 5 min solving an ac optimal power flow problem and was tested in QSTS simulation. At the distribution level, a voltage control algorithm dispatches reactive power from DERs with the goals of meeting subtransmission service requirements and satisfying all the constraints at the distribution side. A power hardware-in-the-loop (PHIL) architecture to test the influence of volt/var controls in PV inverter on feeder voltages has been proposed [44, 45]. The architecture includes advanced PV inverters with reactive power control located at the National Renewable Energy Laboratory's Energy Systems Integration Facility, the open-source GridLAB-D distribution modeling platform supporting real-time synchronization and QSTS simulation at PNNL's Electricity Infrastructure Operations Center, and communication link between the National Renewable Energy Laboratory's PHIL simulation and PNNL's GridLAB-D distribution system model. This PHIL architecture showed the flexibility required to interconnect different facilities for slow system phenomena captured by QSTS [45].

Short circuit analysis has traditionally been performed by estimating short circuit currents based on contribution from synchronous machines and electric motors [46]. These algorithms have been used for quickly screening and studying system strength and evaluating circuit breakers as part of system planning studies. The algorithms are challenged by the fact that power electronics-based devices do not have a standard or unique way of contributing to short circuit currents [47]. Presently, the contribution from power electronics devices is dependent upon the vendor, which may consider the limitations of the semiconductor devices present, the standards, or a combination of both.

NERC recommends that transmission operators understand areas of concern with low SCR and that they establish sufficient requirements to integrate power electronics-based resources [48]. To study SCR and system strength as part of the integration of large amounts of renewable generation, the following approaches maybe applied:

- Expanded new SCR metrics derived from traditional SC studies were applied as screening methods for ERCOT [49], NERC [50], and MISO [51]. These metrics are recommended to gain a high-level understanding of the potential issues that could arise from integrating power electronics–based resources [50].

- Simulations with EMT models instead of using traditional short circuit algorithms were performed in AEMO, Australia [52]. NERC suggests that transmission planners may consider using EMT models after SCR screening [50].

- New algorithms and metrics have been proposed in the literature [53].

These studies may help identify solutions like dynamic compensation requirements (synchronous compensation, FACTS, HVdc) [49], [51] to strengthen the grid. For example, AEMO proposed a solution criterion for weak grid issues through establishment of a minimum requirement of online synchronous machines [52]. Other solutions strategies could include also enhancing controls of inverter-based resources [50]. The steady-state simulation studies are summarized in Table ES-3 below.

Table ES-3. Summary of studies using steady-state simulation tools.

Power Flow	Transmission and Distribution (T&D) Power Flow Cosimulation	QSTS	Short Circuit
• Need for advanced algorithms for high penetration of dc lines and networks. • Wind and solar plant representations have been developed. • Ongoing industry development of data sets and models for high penetration of DER. • NERC currently requires contingency analysis every 30 min.	• Increased need for T&D power flow cosimulation as increased penetration of DER makes distribution systems more dynamically active. • For accuracy in cosimulation, solution should iterate between T&D models, which increases the computational burden. • Meeting NERC contingency analysis requirements with T&D cosimulation becomes more challenging.	• Most QSTS efforts concentrated in distribution. • With high penetration of renewables QSTS modeling needs could also appear in subtransmission (as in recent study) and transmission. • Initial efforts have researched QSTS with HIL simulations. • Initial efforts focused on an adaptive QSTS simulation that switches to and from TS dynamics when needed.	• Algorithms for screening system strength and evaluating circuit breakers as part of system planning. • Power electronics–based devices do not have a standard or unique way of contributing to fault currents (vendor dependent). • Expanded new SCR metrics derived from traditional system to gain a high-level understanding. • EMT simulations recommended.

2. EXISTING CAPABILITIES

2.1 COMPONENT SIMULATION TOOLS (OFFLINE/REAL-TIME)

Some of the component simulators include MATLAB/Simulink/SimPowerSystems (SPS), PSCAD, Piecewise Linear Electric Circuit Simulation (PLECS), Power electronics Simulator (PSIM), Linear Technology Simulation Program with Integrated Circuit Emphasis (LT SPICE), among others. These simulators have typically been used to simulate components like power electronics and semiconductor devices. The typical simulation of duration of components is hundreds of milliseconds to two seconds with a time step on the order of nanoseconds to microseconds. The number of states simulated is on the order of tens of thousands (with a maximum of 50,000 estimated), and the time taken to simulate ranges from 1 min to 10 h [28, 29].

The real-time component simulators include eFPGASIM, Real-time Digital Simulator Computer Aided Design (RSCAD®), Typhoon, among others. They have the capability to simulate up to 128 switches/FPGA [54] and up to 6,000 submodules (SMs) in a modular multilevel converter (MMC) in real-time [55, 56]. The typical time step is on the order of several hundreds of nanoseconds. The number of states per unit simulated is on the order of hundreds to thousands (with a maximum of up to 18,000 estimated) [57, 58]. The total number of states simulated is on the order of tens of thousands (with a maximum of 25,000 estimated) [59]. Component-EMT cosimulation is feasible using eFPGASIM and eMEGASIM [60] and RSCAD® substep high-fidelity simulation [61].

2.2 EMT TOOLS (OFFLINE/REAL-TIME)

Some of the time domain EMT simulators include Power System Computer Aided Design (PSCAD), ElectroMagnetic Transient Program (EMTP)-RV, SPS, PSS®SINCAL, DIgSILENT PowerFactory, Electrical Transient and Analysis Program (ETAP), Alternative Transient Program (ATP), among others. These simulators have typically been used to simulate fast transients associated power electronics hardware, study insulation coordination, and perform stability analysis on smaller transmission or distribution systems that are on the order of 1,000 nodes or buses in size. The typical duration of simulation is up to 30 s with a time step of 1–50 μs. The number of states simulated is on the order of millions (with a maximum of up to 7 million estimated), and the time taken to simulate ranges from 2.25 to 5 h [25, 26]. Additionally, there are capabilities to perform hybrid EMT-TS simulation through software like E-Tran that connects PSCAD to Power System Simulator for Engineering (PSS®E), PSS®SINCAL, DIgSILENT PowerFactory, and EMTP-RV, among others. The estimated number of boundary buses simulated in hybrid simulations is in the tens (with a maximum of up to 25 estimated based on publicly available information) [28, 62, 63].

The real-time EMT simulators that are available commercially include RSCAD®, HYPERSIM, eMEGASIM, Typhoon, among others. They have the capability to simulate up to 9,000 three-phase nodes in 270 cores in real-time with 10–100 μs time steps [64]. The number of nodes per core in real-time simulation is up to 30–40 nodes/core [60, 57]. The typical time step is on the order of 10–100 μs. The number of states per unit simulated is on the order of tens of thousands (with a maximum of 17,000 estimated). The total number of states simulated is on the order of millions (with a maximum of 4.5 million estimated). There are capabilities to perform hybrid EMT-TS simulations using ePHASORSIM and eMEGASIM [60], RSCAD® [65], Open Distribution System Simulator (OpenDSS), and Typhoon [66], among others.

2.3 TS SIMULATION TOOLS (OFFLINE/REAL-TIME)

Several TS simulators currently exist, including PSS®E, Positive Sequence Load Flow (PSLF), EMTP-RV, EUROSTAG®, CYME, NEPLAN, PowerWorld, DIgSILENT PowerFactory, Power System Analysis Toolbox, Transient Security Assessment Tool (TSAT), ETAP, and others that. These programs have the capability to simulate balanced regional/continental transmission networks with up to 150,000 buses, and these simulators can perform positive-sequence phasor-domain simulations. They have been typically used to perform contingency analysis, stability analysis, protection coordination analysis, among others. There are TS simulators that can perform three-phase phasor-domain simulations like PSS®SINCAL, DIgSILENT PowerFactory, NEPLAN, CYME Distribution Analysis (CYMDIST), OpenDSS, GridLAB-D^{TM}, and others that can simulate several thousands of nodes. The typical duration of simulation in TS simulators is up to 60 s with a time step of millisecond(s). The number of states simulated is on the order of millions (with a maximum of up to 3.5 million estimated) and the time taken to simulate ranges from 0.5 to 1 h [28].

The real-time TS simulators available in market include ePHASORSIM, RSCAD®), among others. They have the capability to simulate up to 10,000 nodes per core in real-time with a typical time step of 1–20 ms [60]. The typical time step is on the order of 1–20 ms. The number of states per unit is on the order of tens of thousands (with a maximum of 21,000 estimated). The total number of states simulated is on the order of hundreds of thousands (with a maximum of 220,000 estimated) [60].

The characterization of the existing dynamic simulators and real-time dynamic simulators are provided in Tables 4 and 5 below.

Table ES-4. Characterization of the existing dynamic simulators.

Type of Simulator (Time-Steps)	Duration of Simulation	Modeling Domain (Simulator Examples)	Grid Simulated	Size of Study System	Typical Time Taken to Simulate	Type of Studies Performed
TS simulator (~ms)	~60 s	Positive sequence phasor-domain (PSS®E, PSLF, ETAP, EMTP-RV, PowerFactory, TSAT	Transmission; Balanced	Regional/ Continental (Up to 150,000 buses)	0.5–1 h (up to 3.5 million states estimated to be simulated)	Contingency analysis, stability analysis, protection analysis
		Three-phase phasor-domain (PSS®SINCAL, PowerFactory, GridLAB-D™)	Distribution; Unbalanced	Local (Several 1,000s of nodes)		
EMT simulator (~1–50 µs)	~30 s	Three-phase time domain (PSCAD, EMTP-RV, SPS, PSS®SINCAL, DIgSILENT PowerFactory, ETAP, ATP)	Small transmission, distribution, residential, microgrids; Balanced, Unbalanced;	Small number of nodes (studied up to 1,000 buses)	2.25–5 h (up to 7 million states estimated to be simulated)	Power electronics hardware studies, insulation studies, protection/ stability studies
Component simulator (~ns–µs)	~100s ms –2 s	Three-phase time domain (PLECS, PSim, LT Spice, SPS, PSCAD)	Components (like power electronics and semiconductor devices)	A few nodes with power electronics system(s)	1 min to 10 h (up to 50,000 states estimated to be simulated)	Power electronics hardware studies
TS simulator	Positive-sequence phasor-domain (ePHASORSIM, RSCAD®)	Transmission, distribution; Balanced, unbalanced.	10,000 nodes/core (max: 30,000 nodes)	Typical: 1–20 ms	Per Unit: 10,000s/unit (maximum: 21,000 estimated), Total: 100,000s (maximum: 220,000 estimated)	T&D interactions, system of power converters, protection coordination, cyber-secure (physical) systems

Table ES-5. Characterization of the existing real-time dynamic simulators.

Type of Simulator	Modeling Domain (Simulator Examples)	Grids Simulated	Size of Study System	Time-steps	States Simulated	Type of Studies Performed
EMT simulator	Three-phase time domain (eMEGASIM, HYPERSIM, RSCAD®, Typhoon)	Transmission, distribution, microgrids; Balanced, unbalanced.	30–40 three-phase buses/core (max: 9,000 three-phase nodes/270 cores tested)	Typical: 10-100 µs	Per Unit: 10,000s/unit (maximum: 17,000 estimated) Total: 1,000,000s (maximum: 4,500,000 estimated)	Passives, control system, cyber-secure (physical) systems for components, power converter, system of power converters
Component simulator	Three-phase time domain (eFPGASim, RSCAD®, Typhoon)	Components (Power electronics hardware)	128 switches/ FPGA (max: 6,000 SMs in MMCs)	Typical: 100s ns	Per Unit: 100-1,000s/unit (maximum: 18,000 estimated) Total: 10,000s (maximum: 25,000 estimated)	Modular power electronics, control system, power converter

2.4 POWER FLOW SIMULATION TOOLS (OFFLINE/REAL-TIME)

Some of the examples of positive-sequence balanced power flow simulators include PSS®E, PSLF, EMTP-RV, EUROSTAG®, CYME, NEPLAN, PowerWorld, DIgSILENT PowerFactory, Power System Analysis Toolbox, Powerflow & Short circuit Assessment Tool (PSAT), ETAP, Pandapower, MATACDC, and others that have the capability to simulate balanced regional/continental transmission networks with up to 150,000 buses in the transmission system. They have been used to perform full network analysis and contingency analysis that relates to identification of thermal and voltage limits, among others. There are three-phase power flow simulators like PSS®SINCAL, EMTP-RV, DIgSILENT PowerFactory, NEPLAN, CYMDIST, OpenDSS, GridLAB-D™, and others that can simulate up to 8,500 nodes in the distribution system. These simulations are typically at a specific snapshot in time domain. The number of states simulated is on the order of thousands (with a maximum of 160,000 estimated), and the EI grid described in [28] takes seconds to simulate.

2.5 QSTS SIMULATION TOOLS (OFFLINE/REAL-TIME)

The QSTS simulation tools, such as DIgSILENT PowerFactory, ETAP, among others, provide the capability to perform network analysis with renewables variability in transmission systems. These tools are based on positive-sequence phasor-domain analysis. They have been used to evaluate regional grids with up to 3,300 buses [42]. The typical time step can range from 1 to 300 s, and the duration of simulation can be days to years. There are three-phase QSTS simulation tools like DIgSILENT PowerFactory, OpenDSS, GridLAB-D™, among others, that can simulate up to 8,500 distribution nodes [67]. These QSTS simulations can be run in faster-than-real-time depending on the size and simulation time steps.

Real-time QSTS simulation is a new development. For example, there is ongoing research on GridLAB-D™ that enables real-time simulations to analyze distribution grids with solar penetration and to evaluate demand response. This capability can study up to 8,500 nodes with a time step ranging between 1 and 60 s. It has been evaluated to perform cosimulations with PHIL capability [67].

The characterization of the existing steady-state simulators and real-time simulators are provided in Tables 6 and 7 below.

Table ES-6. Characterization of the existing steady-state simulators.

Type of Simulator (Time-Steps)	Duration of Simulation	Modeling Domain (Simulator Examples)	Grid Simulated	Size of Study System	Typical Time Taken to Simulate	Type of Studies Performed
Power flow studies (~1–300 s)	Snapshots	Positive sequence phasor-domain (PSS®E, PSLF, PowerFactory, Pandapower, MATACDC)	Transmission; Balanced	Regional/ Continental (Up to 150,000 buses)	On the order of seconds (up to 160,000 states estimated to be simulated)	Full network analysis, contingency analysis (thermal, voltage)
		Three-phase phasor-domain (PSS®SINCAL, PowerFactory, OpenDSS, GridLAB-D™)	Distribution; Unbalanced	Local (Up to 8,500 nodes)		Full network analysis, reconfiguration analysis
QSTS (~1–300 s)	~days to years	Positive sequence phasor-domain (ETAP, PowerFactory)	Transmission; Balanced	Regional (Up to 3,300 buses)	Faster-than-real-time based on size of network and simulation time step	Network analysis (with renewables variability)
		Three-phase phasor-domain (PowerFactory, GridLAB-D™, OpenDSS)	Distribution; Unbalanced	Local (Up to 8,500 nodes)		Demand response, distribution analysis with solar

Table ES-7. Characterization of the existing steady-state simulators.

Type of Simulator	Modeling Domain (Simulator Examples)	Grids Simulated	Size of Study System	Time-steps	Type of Studies Performed
QSTS studies	Three-phase unbalanced power flows (GridLAB-D™)	Unbalanced; Distribution	8,500 nodes	Time step 1–60 s	Distribution analysis with solar, demand response

2.6 HARDWARE-IN-THE-LOOP SIMULATIONS

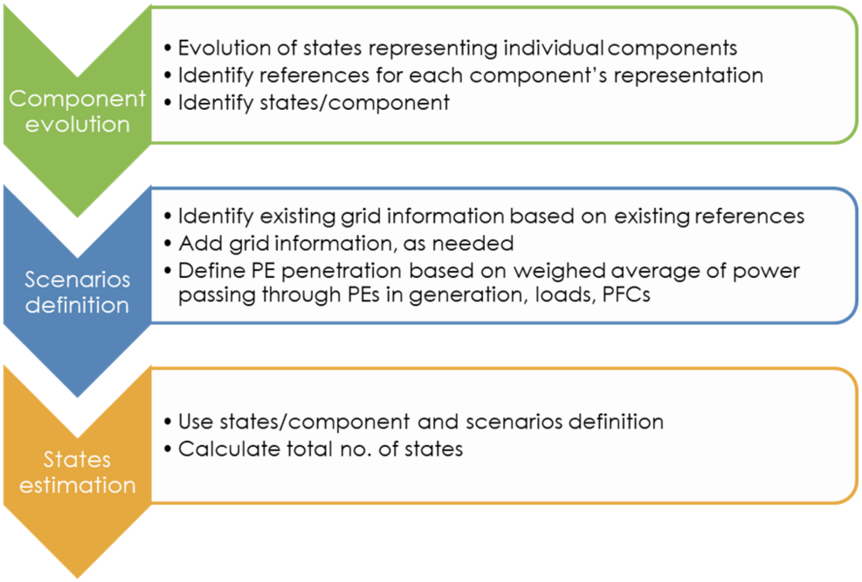
Physical parts of a system are evaluated in HIL simulations, which enable testing and evaluation of the physical parts. The physical parts can be control systems, power electronics building blocks, power electronics systems, relays and breakers, among others. The following table (Table ES-8) illustrates some of the HIL simulators being used.

Table ES-8. Overview of HIL simulators.

Location	Power Amplifier Ratings	Test Results from Publications	Frequency Rating	Operating modes
Clemson University	15 MW, 24 kV grid simulator (~ms speed)	4.16 kV, 2.2 MW	45–65 Hz	AC
Center for Advanced Power Systems – Florida State University	5 MW, 24 kV (~ms speed)		DC	DC
	5 MVA, 4.16 kV (~ms speed)	500 kVA, 4.16 kV	45–65 Hz	AC
Idaho National Laboratory	60 kVA, 520 V grid simulator (~ms speed)	N/A	30–100 Hz	4 quadrants
National Renewable Energy Laboratory	1 MVA, 520 V grid simulator (with 90 kVA × 12 grid simulators, ms speed)	80 kVA, 480 V	16–820 Hz	AC (90kVA), DC (60KW) per unit
	7MVA, 13.2kV grid simulator	7 MVA, 13.2 kV	45–60 Hz	AC
Oak Ridge National Laboratory	Modules (2 kV, 20 A) in large power electronics system evaluator (PE-HIL part of FIRE platform)	2 kV, 20 A	Up to 120 Hz	AC + DC with square-wave voltages from modules
	360 kVA, 480 V grid simulator (~ ms speed)	N/A	16–820 Hz	AC (90kVA), DC (60KW) per unit
	Device evaluation and characterization (10 kV, 15 A) for semiconductor devices characterization		Double pulse	
Sandia National Laboratories	180 kVA, 520 V grid simulator (~ ms speed)	N/A	16–820 Hz	AC (90kVA), DC (60KW) per unit

3. SCENARIOS, EVENTS DESCRIPTION, FUTURE GRID REQUIREMENTS, AND STANDARDS SUMMARY

The scenarios of future grids and evolution of the component models in the grid identify the characteristics of future simulators and real-time simulators. The scenarios considered in this study are defined in Section 3.1. The evolution of the component models is based on historical evolution of models (explained in Section 3.2) and the complexity of the components expected in the future scenarios. The complexity of the component models is briefly summarized in Sections 3.3 and 3.4 for dynamic and steady-state simulators, respectively. Based on the evolution of the components and defined scenarios, the number of states that need to be simulated is estimated for future scenarios. The method is summarized in Figure ES-4.



- Evolution of states representing individual components
- Identify references for each component's representation
- Identify states/component

- Identify existing grid information based on existing references
- Add grid information, as needed
- Define PE penetration based on weighed average of power passing through PEs in generation, loads, PFCs

- Use states/component and scenarios definition
- Calculate total no. of states

Figure ES-4. State estimation method for studying future scenarios of grid.

3.1 SCENARIOS AND EVENT DESCRIPTION

There are three scenarios being considered in this report. They include: (i) up to 20% penetration of power electronics (the *traditional power system*), (ii) 20–50% penetration of power electronics (the *intermediate scenario*), and (iii) 50–100% penetration of power electronics (the *future scenario*). The term *penetration of power electronics* is defined in the section above. The characteristics of each scenario are summarized in Table ES-9.

Some of the challenges anticipated with higher penetration of power electronics include control interactions, subsynchronous interactions, increased sensitivity of power electronics to external disturbance that may affect the stability of the grid, low SCR, voltage variability, reduced inertia, among others. Some of these challenges have been highlighted by the NERC studies [18, 19, 20], MISO study [51], ERCOT study [25], and AEMO study [26]. As the penetration of power electronics increases, other challenges may arise.

Table ES-9. Summary of characteristics of future scenarios.

Characteristics	Traditional Power System	Intermediate Scenario: Power Electronics and Traditional Components	Long-Term Scenario: High-Penetration Power Electronics
Electrical Components	*Generators:* Synchronous generators, low penetration of wind/PV plants/ DERs	*Generators:* Synchronous generators, variable-speed drives in synchronous generators, medium penetration of wind/PV/Energy Storage (ES)/DERs	*Generators:* power electronics sourced generations (wind, PV, ES, variable-speed drives connecting to conventional sources like steam turbines, hydroelectric turbines, etc.), DERs
	Transformers: Tap-changing transformers, uncontrolled 60 Hz transformers	*Transformers:* Uncontrolled 60 Hz transformers, distribution SSPS 1.0 [68]	*Transformers:* SSPS 3.0 with power electronics controlled transformers [68]
	Power Flow Controllers and Reactive Power Compensators: Few HVdc lines, more static VAR compensators and uncontrolled reactor banks than stationary compensators (STATCOMs) or static synchronous series compensators (SSSC)	*Power Flow Controllers and Reactive Power Compensators:* More HVdc, more power electronics-based FACTS/ Distribution-FACTS (D-FACTS) like smart wires, STATCOMs, and SSSCs, and lesser mechanically switched, uncontrolled reactor banks	*Power Flow Controllers and Reactive Power Compensators:* HVdc, MVdc, power electronics-based FACTS, power electronics-based D-FACTS, fault limiters
	Protection: Mechanical breakers	*Protection:* Mechanical breakers, hybrid breakers	*Protection:* Solid-state breakers, hybrid breakers
	Loads: Machine-based loads (induction machines), low penetration of DERs/ES/electric vehicle (EV) chargers, incandescent lighting	*Loads:* Machine-based loads (induction machines), medium penetration of DERs/ES/variable-speed drives, high penetration of wired fast EV chargers, solid-state lighting	*Loads:* Variable-speed drives, extreme fast EV chargers (wired and wireless) with power electronics, DERs/ES, solid-state lighting
Control and Communication	*Transmission Communication:* 1 G Ethernet for supervisory control and data acquisition (SCADA) from field sensors (programmable logic controllers – PLCs, remote terminal units – RTUs, phasor measurement units – PMUs) *Distribution Communication:* Limited communication present with switches and RTU data exchanges	*Transmission Communication:* 100 G Ethernet for SCADA *Distribution Communication:* 100 G Ethernet for real-time data exchange from DERs, feeders (and greater sensor deployment), smart loads	*Transmission Communication:* Very high-speed communication *Distribution Communication:* Very high-speed communication from DERs, feeders, smart loads, smart buildings

Table ES-9. Summary of characteristics of future scenarios (continued).

Characteristics	Traditional Power System	Intermediate Scenario: Power Electronics and Traditional Components	Long-Term Scenario: High-Penetration Power Electronics
	Transmission Control: Central energy management system (EMS), human machine interface (HMI), and decentralized voltage/ frequency control in transmission systems *Distribution Control:* Control switches to change configuration	*Transmission Control:* Automated EMS with minimum human interaction *Distribution Control:* DER management system (DERMS), advanced distribution management system (ADMS) *Microgrid Control:* Microgrid Central Controller (MGCC)	*Control:* Centralized-Decentralized control in nanogrids-microgrids-distribution-transmission systems
	Sensors: PLCs, RTUs, PMUs in transmission systems. There are few digital fault recorders (DFRs). Limited sensors in distribution systems.	*Sensors:* PLCs, RTUs, PMUs with increased bandwidth in transmission systems. Increased presence of distribution PMUs, digital fault recorders (DFRs), and other high bandwidth sensors in distribution/transmission.	*Sensors:* High bandwidth sensors in distribution/ microgrids/transmission/ nanogrids (buildings).
Interconnections	Heavily interconnected system	Interconnected with a percentage of asynchronous islanded systems (and potentially can dynamically island)	Asynchronous, decoupled, firewalled, fractal sections [68]

3.2 MODEL COMPLEXITY

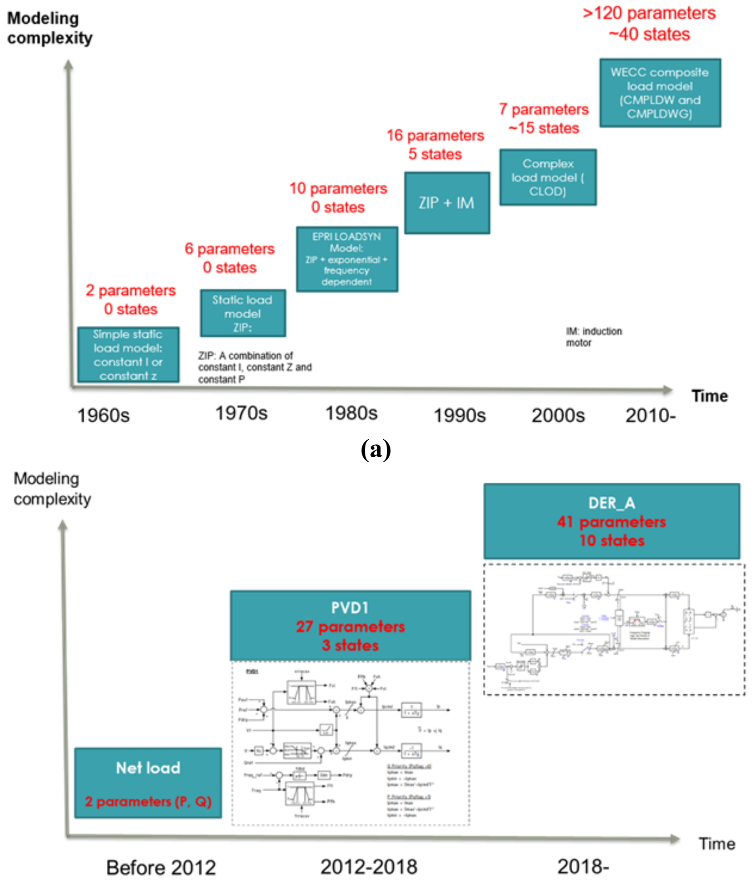
In recent history, an evolution and significant increase of modeling complexity have been observed in industry's modeling practice. The increase in complexity has been observed in renewable generation modeling and more significantly in the load models. Such evolution of industry-grade models is a motivation for our investigation of modeling gaps and illustrates the modeling process evolution in the power industry. Three aspects are briefly discussed:

1. Evolution of complexity in loads (Figure ES-5 [a]): When computer-based power system simulation emerged in 1960s–1980s, the static load models [69] were adopted. The complexity of the static load model increased from 1960s to 1980s. After the 1996 North America blackout, engineers realized that the static load models are inadequate for reproducing low-frequency power oscillations [70]. Therefore, a prototype dynamic induction motor model was developed and adopted in combination with static load model [71]. After the 2000s, Siemens Power Technologies International (PTI) adopted a more complex composite load model explicitly representing aggregations of large and small motors, nonlinear models of discharge lighting, transformer saturation effects, constant megavolt-ampere, shunt capacitors, and a series impedance and tap ratio to static load models in [69]. However, this model is unable to reproduce the fault-induced delayed voltage recovery (FIDVR) phenomenon caused by cascaded stalling of residential air conditioner motors. To represent FIDVR, WECC initiated a load modeling task force (LMTF) involving several utilities, national laboratories, and a General Electric (GE) PSLF vendor to co-develop a WECC composite load model (CMPLDW) that includes an aggregate air conditioner model as one component [72].

2. Adding dynamic models of DERs to load models (Figure ES-5 [b]): Recently, DERs became more prevalent in distribution feeders. This led to an aggregate DER model being explicitly added to the composite load model CMPLDW [73]. The new WECC composite load model (CMPLDWG) that includes DER_A controls has more than 160 parameters (CMPLDW + DER_A) and is the most sophisticated transmission-level load model implemented in various power system TS simulators.

3. Evolving modeling of renewable generation (Figure ES-6): In the early 2000s, development of the first generation of dynamic generic models for renewables started in WECC. In 2010, WECC started the development of the second generation of generic models [74]. In parallel, in 2010, the International Electrotechnical Commission (IEC) started a similar modeling effort. WECC started formally adopting the models in late 2014 and early 2015, and by this time the vast majority of the first generation of generic models had been replaced in the WECC official database. Adoption of these models in the EI has been slower. Since 2016, the WECC revisited the second generation of generic models and proposed modifications to further improve their applicability [75], [76]. The generic models currently have several shortcomings, especially for weak grids with high penetration of renewable generation, as discussed in [77]. To resolve these shortcomings, it is expected that modeling complexity for renewable generation will continue to evolve, likely into more detailed models.

Similar to the power grid's evolution, the models are expected to evolve as increasing levels of power electronics-based equipment are installed.



(a)

(b)

Figure ES-5. Evolution of Load and Distributed Generation Models.

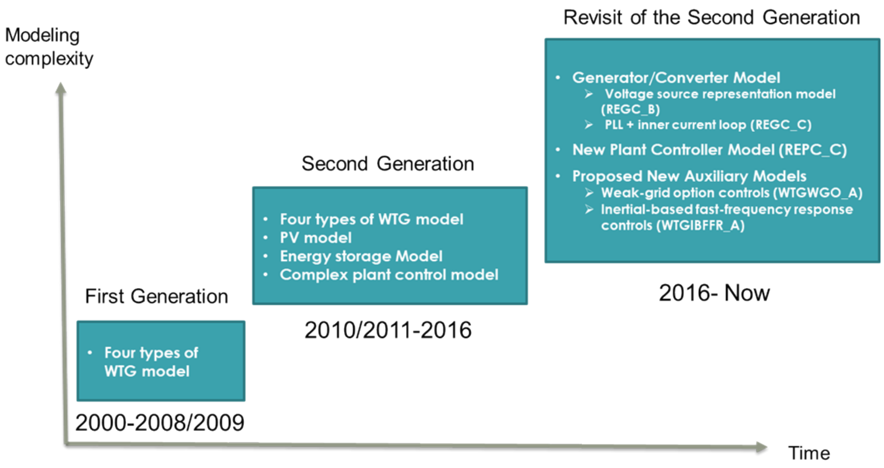


Figure ES-6. WECC generic renewable dynamic models evolution.

3.3 DYNAMIC SIMULATION STUDY REQUIREMENTS

Component Simulation Tools: The increased requirements in component simulators for future scenarios arise from the advances in semiconductor technology that has increasingly adopted the wideband gap semiconductor devices like silicon carbide (SiC) and gallium nitride (GaN). The SiC and GaN semiconductor devices can switch much faster than the traditional silicon (Si) semiconductor devices, thereby reducing the time step required in component simulations. Moreover, there is a trend toward high-frequency transformer utilization compared to the traditional 60 Hz bulky transformer in niche applications that may also be used in SSPS 1.0, 2.0, and 3.0. These trends require the utilization of smaller time steps than today's typical time step considered in component simulations. Moreover, the complexity of the power electronics' circuit architecture is expected to increase with increased penetration of power electronics through multilevel converters and dual-active bridge converters, among others. The complexity of the power electronics' models is expected to increase for higher fidelity of models to perform electrical, magnetic, and thermal simulations. These complexities will increase the number of states simulated in component simulations. The time taken to simulate will need to be reduced to enable enhanced utilization of the component simulation tools that can simulate high-fidelity models of complex power electronics. The changes desired in time steps, number of states to be simulated, and time taken to simulate will also enable faster-than-real-time component simulation that can be used in digital twins of components for predictive maintenance and diagnostics.

The real-time simulation tool to simulate components will require the corresponding changes in time-steps. It will also require increased number of states to be simulated per unit and total number of states simulated. While the former accounts for faster switching semiconductor devices and the complexity of power electronics' circuit architecture, the latter accounts for increased fidelity of models and complexity of power electronics' circuit architecture. The real-time simulation tool to simulate components will be used to evaluate modular power electronics, passives, control systems of components, cyber-security systems in components, single power electronics equipment, among others, in HIL configuration.

EMT Simulation Tools: Based on the challenges observed with local high-penetration of power electronics that have been studied in California and by ERCOT, NE-ISO, AEMO, and others, there is an increasing need for EMT simulation of larger systems to study contingencies, stability of systems, protection systems, power electronics hardware and control interactions, resilience, and fast real-time scheduling. The larger systems may include the local transmission systems with detailed distribution systems, regional transmission systems, among others in the intermediate scenario, and larger continental size transmission systems, regional transmission systems with detailed distribution systems, among others in the future scenario. Moreover, the fidelity of individual component model will also be increased to study high bandwidth responses and sensitivities to external disturbances observable in such systems. The increased fidelity also arises from complex power electronic circuits. The increased fidelity of the models will be observed in the models of power electronics, transformers, transmission lines, among others. The power electronics will be present in SSPS 1.0, utility-scale power electronics-based generations, DER power electronics, and loads like EV chargers in the intermediate scenario. The power electronics will be present in SSPS 3.0, SSPS 2.0, SSPS 1.0, power electronics-based generations, DER power electronics, and loads like EV chargers and variable-speed drives. Based on these trends, the number of states simulated in EMT simulations will increase tremendously. These are calculated based on the intermediate and long-term scenarios with the complexity introducing by improved fidelity of models incorporated. The time step of EMT simulations will also change with the high bandwidth components in the grid that include the high-frequency transformers, wideband gap device based faster power electronics, among others. The time taken to simulate needs to be decreased to the time taken by conventional TS simulations for improved utilization of the EMT tools. The changes desired in time steps, number of states to be simulated, and time taken to simulate will also enable faster-than-real-time EMT simulation of smaller regions that are not feasible today in operational tools like online dynamic security assessment (DSA) tools.

The real-time simulation tool to perform EMT simulations will require the corresponding changes in time steps. It will also require increased number of states per unit and total number of states. Although the former accounts for the need to simulate higher bandwidth components and possible control interactions between the components, the latter accounts for the need to simulate larger systems with higher fidelity models. The real-time EMT simulation will be used to evaluate the interaction of the control system in a single power electronics system with the grid, interaction of multiple control systems in multiple power electronics, stability and interactions of hierarchical control system (like EMS and the distribution management system – DMS) in transmission-distribution systems, protection coordination in transmission-distribution systems, cyber-security systems in transmission-distribution systems, among others.

Hybrid EMT-TS Simulation Tools: There will also be an increasing trend toward reducing the computational burden of performing very large-scale EMT simulations by using hybrid EMT-TS simulations. To study future scenarios, the number of boundary buses will need to be increased in such simulations in future scenarios that can be estimated based on one such scenario studied in [28]. These simulations can be used for contingency analysis, stability analysis, protection analysis, and resilience studies.

TS Simulation Tools: There will be continued need for TS simulations of future scenarios to perform contingency analysis, stability analysis, protection analysis, resilience studies, and fast real-time dispatch scheduling. The increased penetration of distributed generation will necessitate integrated transmission-distribution system studies over large areas that could be an interconnection or several asynchronous interconnections that are connected through direct current (dc) links. These requirements will result in increased number of states that need to be simulated along with the reduction in time steps to account for reduced inertia from distributed generation. Moreover, the time taken to simulate can be reduced through advances in computing solutions. The changes desired in time steps, number of states to be simulated, and time taken to simulate will also enable faster-than-real-time TS simulation of larger systems and/or higher number of contingencies that are not feasible today in operational tools like online DSA tools.

The real-time simulation tool to perform TS simulations will require increased number of states per unit and total number of states. Although the former accounts for the reduced inertia introduced by increased distributed generation and the requirements to simulate distribution grids, the latter accounts for the need to simulate larger systems. The real-time TS simulation will be used to evaluate the stability and interactions of hierarchical control system (like the EMS and DMS) in transmission-distribution systems, protection coordination in transmission-distribution systems, cyber-security systems in transmission-distribution systems, among other uses. In some cases, tools that perform hybrid EMT-TS simulations in real-time may be used.

The discussions in this section are summarized in Table ES-10.

Table ES-10. Summary of dynamic study requirements in future grids.

Study-of-Interest	Modeling Domain	Study System Size	Timescales	Duration of Simulation	Cosimulation	Model Requirements
Contingency analysis (e.g., N-1-1/N-1, faults, response from faults like FIDVR, generator losses, component losses, large contingencies – cascading events, etc.)	Time domain	Can be large area ~1,000,000s nodes	EMT (TS)	Seconds to 1 min	EMT-TS is a possibility	TS models of generators, three-phase EMT models of components (including power electronics-based generations, transformers, sources), detailed transmission line models, protection system models.
Stability analysis (e.g., negative impedances, control interactions, subsynchronous resonances)	Time domain	Can be large area ~1,000,000s nodes	EMT (TS)	Seconds to 1 min	EMT-TS, with TS of generators and EMT of systems/ components	TS models of generators, three-phase EMT models of components (including power electronics-based generations, transformers, sources), detailed transmission line models.

Table ES-10. Summary of dynamic study requirements in future grids (continued).

Study-of-Interest	Modeling Domain	Study System Size	Timescales	Duration of Simulation	Cosimulation	Model Requirements
Protection analysis (ac-dc, dc only, dynamic and adaptive strategies)	Time domain (Phasor-domain)	Can be small-area or large-area ~1,000,000s nodes	EMT (TS, PF)	Seconds to 1 min	EMT-TS PF snapshots (short circuit analysis)	Full three-phase with detailed power electronics models; average-value models; subtransient impedances in short circuit analysis (PF).
Power electronic hardware studies (e.g., HVdc, SSTs, MVdc)	Time domain	Can be in a smaller area ~100,000 nodes	EMT	Milliseconds to seconds	EMT-Component models	Three-phase EMT models with detailed power electronics models, subcomponent detailed models (e.g., semiconductors, inductors, etc.).
Resilience studies (e.g., black start, degrade gracefully, islanding, etc.)	Time domain	Can be in a small or large area ~1,000,000s	EMT (TS, QSTS)	Seconds to hours	EMT-TS is a possibility (based on duration-area of study) QSTS may be needed for longer durations with EMT-TS for shorter durations	Three-phase EMT models including average-value models/ detailed power electronics models; models of inductors, transformer models, etc.
Fast real-time scheduling (e.g., seconds dispatches in regions)	Phasor-domain	Can be large area ~1,000,000s	TS (PF, QSTS)	Seconds to hours	TS with interactions to quasi-steady state analysis	Full three-phase with new models to represent the faster scheduling.

3.4 POWER FLOW/QSTS SIMULATION STUDY REQUIREMENTS

Power flow: NERC [PNNL 1.2.3-6] currently requires transmission operators and reliability coordinators to perform contingency analysis every 30 min using real-time information. The contingency analysis is currently based on power flow solutions. This means that transmission operators and reliability coordination need to solve algorithms and analyze results of many contingencies within a short time. In addition, T&D simulations, with significantly higher number of buses, are expected to be needed to study the future grid with increased penetration of power electronics devices. Therefore, high performance computation of power flow algorithms with increased complexities are desired. The study requirements are summarized in Table ES-11.

QSTS: Currently QSTS simulations have been largely focused on distribution. In the future grid, QSTS simulation will need to be run considering both transmission and distribution. The networks models increase in complexity and number of buses. Complexity could also increase from the need for iteration between models to accurately capture T&D interactions as well as ac-dc system interactions. The time steps required could become shorter, in the order of seconds, as more variable generation is considered. Finally, the time to simulate could be required to be significantly reduced to allow for analysis in reasonable time. The QSTS requirements in future grids are summarized in Table ES-12.

Table ES-11. Summary of power flow study requirements in future grids.

Study-of-Interest	Modeling Domain	Study System Size	Timescales	Duration of Simulation	Cosimulation	Model Requirements
Evaluation and design of slow controls (Transmission/subtransmission and/or distribution analysis with high penetration of DER—combined ac and dc analysis)	**Transmission:** Phasor – dc systems **Distribution:** Three-phase unbalanced – dc systems	10,000–300,000 nodes	PF - QSTS		T&D	Steady state distribution and/or transmission elements with static control characteristics (including power electronics-based generations, transformers, sources), aggregations of loads or by power electronics decoupling, may include external transmission system and detail modeling of some areas. Chronology of control actions should be captured.
Resilience studies (e.g., black start, degrade gracefully, islanding)	Time domain	Can be in a small or large area ~1,000,000s nodes	EMT (TS, QSTS)	Seconds to hours	QSTS may be needed for longer durations with EMT-TS for shorter durations	Three-phase EMT models including average-value models/ detailed power electronics models; models of inductors, transformer models, etc.
Fast real-time scheduling (e.g., seconds dispatches in regions)	Phasor-domain	Can be large area ~1,000,000s nodes	TS (PF, QSTS)	Seconds to hours	TS with interactions to quasi-steady state analysis	Full three-phase with new models to represent the faster scheduling.

Table ES-12. Summary of QSTS study requirements in future grids.

Study-of-Interest	Modeling Domain	Study System Size	Timescales	Cosimulation	Model Requirements
Contingency analysis (screening of all N-1, N-1-1, and selected N-k (transmission) - including converter outages – could include distributed slack bus)	Phasor – dc systems	Can be large ~70,000–100,000 buses	PF – representative snapshots	T&D	Steady state transmission elements with static control characteristics (including power electronics-based generations, transformers, sources), aggregations of loads or by power electronics decoupling, expanded detail in areas of interest
Reliability analysis (Composite transmission / generation reliability [adequacy] assessment with power electronics reliability)	Phasor – dc systems	Can be large ~70,000-100,000 buses	PF – representative snapshots	T&D	Same as above + power electronics and system elements reliability characteristics
Distribution reconfiguration (N-1 and design of reconfiguration strategies)	Three-phase unbalanced – dc systems	10,000 buses per feeder	PF – representative snapshots	T&D	Steady state distribution elements with static control characteristics (including power electronics-based generations, transformers, sources), aggregations of loads or by power electronics decoupling, may include external transmission system
Evaluation and design of slow controls (Transmission/subtransmission and/or distribution analysis with high penetration of DER - combined ac and dc analysis)	Transmission: Phasor – dc systems Distribution: three-phase unbalanced – dc systems	10,000-300,000	PF - QSTS	T&D	Steady state distribution and/or transmission elements with static control characteristics (including power electronics-based generations, transformers, sources), aggregations of loads or by power electronics decoupling, may include external transmission system and detail modeling of some areas Chronology of control actions should be captured
Short Circuit Analysis (If response current contributions from power electronics is known or standardized – calculation of fault currents in network)	Short circuit static model capturing current contributions	Can be large ~70,000-100,000 buses	Short circuit model	T&D might be useful	Network impedances distribution and/or transmission elements with fault current contribution characteristics (including power electronics-based generations, transformers, sources)

The operational characteristics and studies of future scenarios are summarized in Table ES-13.

Table ES-13. Summary of characteristics of operations and studies in future scenarios.

Characteristics	Traditional Power System	Intermediate Scenario: power electronics & Traditional Components	Long-Term Scenario: High-Penetration Power Electronics
Power Dispatch	Hourly dispatch, with real-time market corrections every 15 and 5 min (and in 1 min under extreme circumstances (e.g., CAISO)	Faster dispatch of some resources (approximately subminutes interval), reversible power flow from residential to distribution	Faster dispatch feasible with high penetration of power electronics (~ s or faster), bidirectional power flow at every layer (distribution-transmission, residential-distribution)
Dynamics	*In minutes:* Tap changers, mechanically switched capacitors, settings in automatic voltage regulator (AVR)	*In minutes/seconds:* Some portions of the system may require shorter time scale assessments due to high penetration of power electronics locally. Others may continue with minutes-based dynamics observed in tap changers, mechanically switched capacitors, etc.	*In seconds:* Fast changing power flows due to variability (e.g., wind, PV) and fasting acting devices
	In seconds: Reactive power flows, voltage controllers, synchronous generators Voltage variability in distribution systems due to DERs	*In seconds/milliseconds/ microseconds:* Depending upon system metrics (like SCR, inertia, power electronics penetration, etc.), studies may need to be performed in subseconds or seconds range	*In milliseconds/ microseconds/nanoseconds:* Dynamics of power electronics will require smaller time steps in simulations

Table ES-13. Summary of characteristics of operations and studies in future scenarios (continued).

Characteristics	Traditional Power System	Intermediate Scenario: power electronics & Traditional Components	Long-Term Scenario: High-Penetration Power Electronics
Study Footprints	*PF/QSTS/TS:* Large system studied using PF and TS simulations. Small distribution or subtransmission networks studied using QSTS. Minimal real-time simulations performed	*PF/QSTS/TS:* More transmission and distribution studies using PF/TS to study impact of distributed generations and controlled flow from power electronics. More QSTS studies to understand the impact of variable generation and EV loads. Online stability assessment methods may use PF/TS for real-time assessments	*PF/QSTS/TS:* Increased penetration of power electronics requires larger transmission-distribution studies with QSTS to study worst-case scenarios. TF studies may be performed on transmission-distribution systems. Online stability assessment methods to use PF/TS for real-time assessments
	EMT: Small systems like substations, insulation coordination, subsynchronous oscillations studied in EMT. Real-time EMT and component simulations performed to evaluate device-under-test performance with smaller systems	*EMT:* Larger system studies (like small-scale transmission network with detailed distribution networks or a portion of transmission networks) in EMT to understand local control interactions, large-scale disturbance impact related reliability studies. HIL studies and online assessments to use real-time or faster-than-real-time EMT simulations with larger systems	*EMT:* Largest footprint of EMT studies than today's or intermediate studies (like large-scale transmission networks or a combination of medium-scale transmission network with detailed distribution networks) to understand stability and reliability of systems. HIL studies and online assessments to use real-time or faster-than-real-time EMT simulations with largest footprint of systems
Distribution/ Customer Systems	*Load Models in Transmission Studies:* Aggregated for transmission studies (e.g., composite load modeling, aggregated DER models emerging) *Gaps:* ES and wind as DERs	*Distribution Systems in Transmission Studies:* Integrated studies of transmission-distribution systems with DERs/ES/EV/power electronics loads in locations with high penetration of power electronics	*Distribution System in Transmission Studies:* Possibility for sections of transmission-distribution systems to be decoupled for PF studies (with minimal power exchange between asynchronous/fractal systems). Detailed distribution system models in dynamics with DERs/ES/EV/power electronics loads
	Distribution Studies: Transmission assumed as ideal sources in distribution studies	*Distribution Studies:* Fidelity of combined machine and power electronics load models need to be identified and used in transmission-distribution studies	*Distribution Studies:* Fidelity of power electronics loads and their interaction with other power electronics needs to be assessed and used in transmission-distribution studies

3.5 STANDARDS SUMMARY

Standards applicable to future grids with increased penetration of power electronics are summarized in Table ES-14. The standards indicate the trend of high-fidelity modeling and EMT simulations of larger systems, as maybe noted in the recent ongoing developments in Institute of Electrical and Electronics Engineers (IEEE) P2800, IEEE/CIGRE B4-82, CIGRE C4-56, to name a few. Other standards, such as IEEE 519, IEEE 1547.7, IEEE 3002.2, and IEEE 1159, help define the study requirements for future grids and the type of simulations considered in this report. Details about power electronics systems and their characteristics can be found in standards like IEEE 1662, IEEE 1676, among others.

Table ES-14. Summary of standards applicable to future grids.

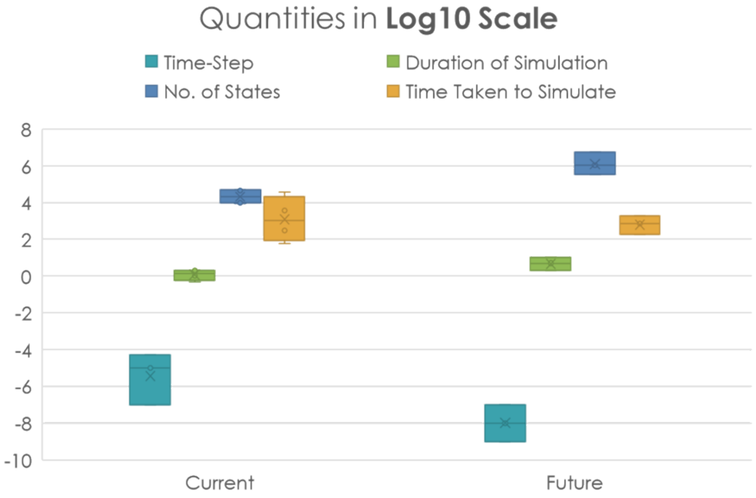
Standard	Name	Key Points Related to this Study
IEEE Std. 1662	IEEE Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems	• **Power electronics equipment studies** needed (power balance, thermal management, transients, dynamic performance) • **Duration and time step** for studies • Types of power electronics equipment **models** needed
IEEE Std 1676	IEEE Guide for Control Architecture for High Power Electronics (1 MW and Greater) Used in Electric Power Transmission and Distribution Systems	• Power electronics equipment **hierarchical control** standards • **Functionalities** of each control stage and time step • **Study** requirements
IEEE Std 1159	IEEE Recommended Practice for Monitoring Electric Power Quality	• Define conducted electromagnetic phenomena
IEEE Std 519	IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems	• **Harmonic standards** for equipment (including power electronics) • **Study** requirements
IEEE Std 1547.7	IEEE Guide for Conducting Distribution Impact Studies for Distributed Resource Interconnection	• Different types of **simulations defined**: power flow, quasi static simulation (QSS/QSTS), dynamic simulation (TS), electromagnetic transient simulation (EMT) for distribution systems
IEEE Std 3002.2	IEEE Recommended Practice for Conducting Load-Flow Studies and Analysis of Industrial and Commercial Power Systems	• **QSTS definition** for transmission systems • **Study** needs identified and defined • Computational challenges and data requirements for QSTS identified
IEEE P2800	Standard for Inverter-Based Resources Connecting to the BPS	• NERC follow-up from reliability concerns identified with inverter-based resources
IEEE/CIGRE B4-82	Guidelines for Use of Real-Code in EMT Models for HVDC, FACTS and inverter-based generators in Power Systems Analysis	• **Real code usage** for control systems in power electronics equipment • Use of switched system model of power electronics equipment
CIGRE C4-56	Electromagnetic transient simulation models for large-scale system impact studies in power systems having a high penetration of inverter connected generation	• Support **large-scale EMT** simulations • Develop standards for models • Increasing trend to use EMT simulations • Computational challenges identified

4. FUTURE GRID SIMULATION GAPS

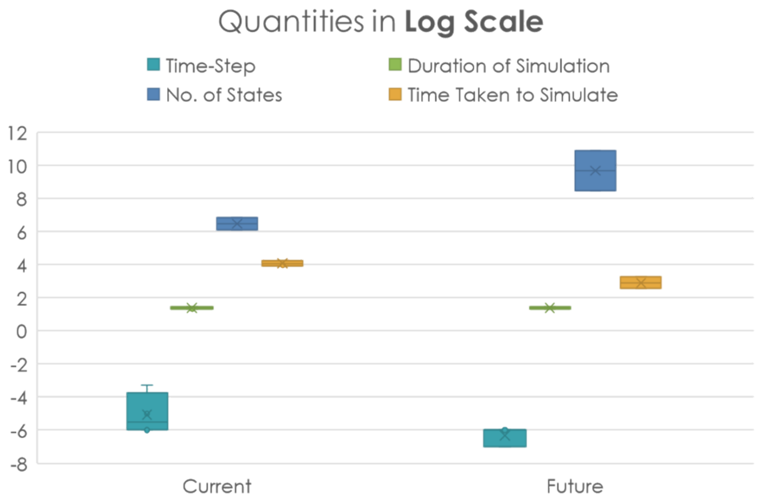
Based on the characteristics of existing tools, studies performed with them, and the required tool characteristics needed to study future scenarios of the grid, gaps are identified for each simulator and are presented in the following subsections.

4.1 DYNAMIC SIMULATOR CHARACTERISTICS

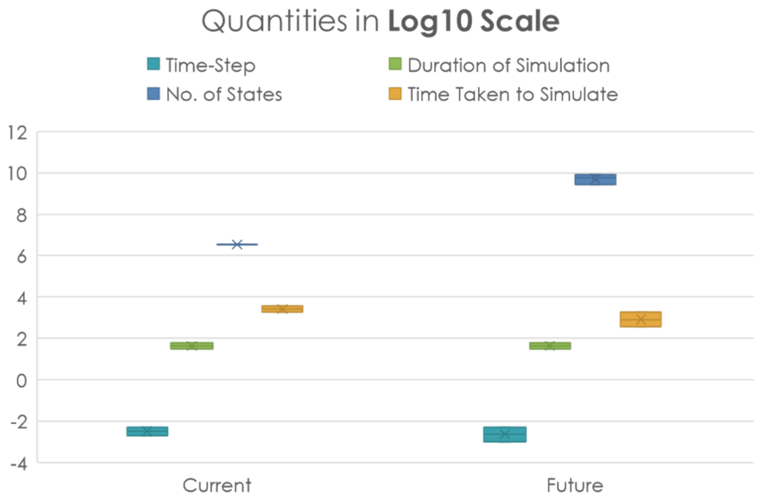
The characteristics of existing dynamic simulators are shown in Figure ES-7 (Current). The range of numbers provided for each characteristic is based on the different studies that have been completed with each simulator. The requirements from the dynamic real-time simulators to study future scenarios of the grid are also shown in Figure ES-7 (Future). The range of numbers provided for each characteristic reflects the different study systems considered in future scenarios. For example, in the intermediate scenario, study systems may include 50% penetration of power electronics in local/regional grids that may represent 10–100% of the interconnection. Similar case studies can also be considered for the long-term scenarios. These study systems in the two scenarios result in the range observed in the characteristics of the dynamic simulators required to study future scenarios grids in Figure ES-7. From Figure ES-7, the trends of requirements in dynamic simulators to study future scenarios of grids include reduced time steps, increased number of states that need to be simulated, and reduced time taken to simulate. For component simulators, increased duration of simulations are also required. These changes are needed because of the future grid scenarios and the high-fidelity models being considered (Section 3).



(a) Component Simulators



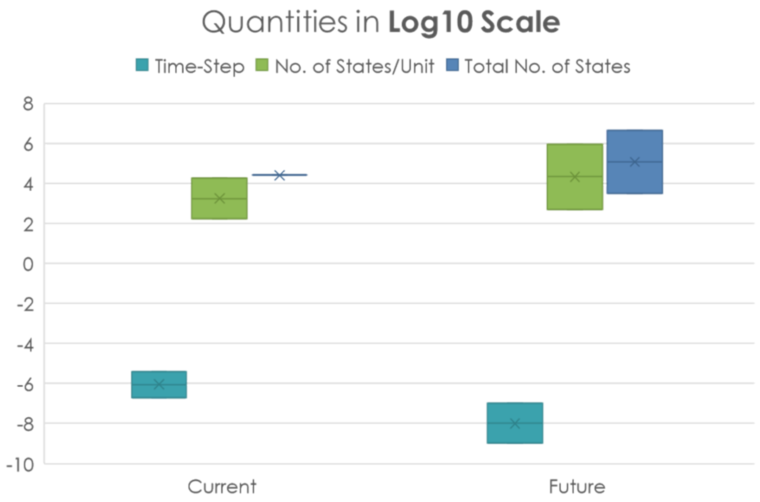
(b) EMT Simulators



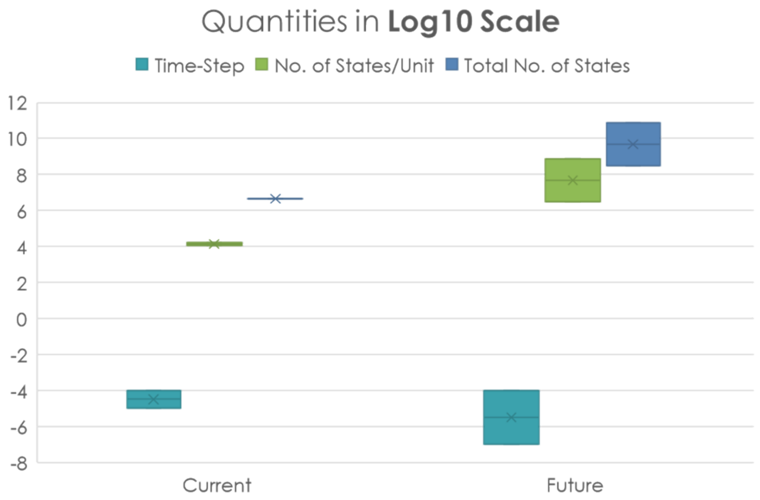
(c) TS Simulators

Figure ES-7. Characteristics of existing dynamic simulators (Current) and the required characteristics in future dynamic simulators (Future).

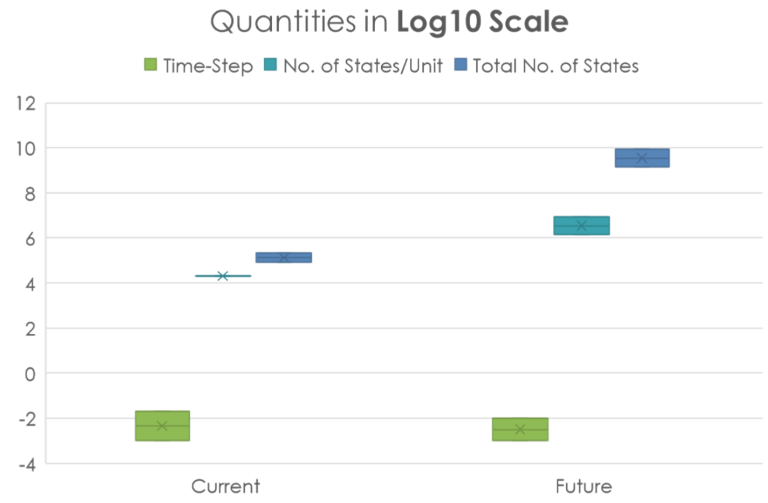
The characteristics of existing dynamic real-time simulators are shown in Figure ES-8 (Current). The requirements from the dynamic real-time simulators to study future scenarios of the grid are also shown in Figure ES-8 (Future). The range observed in Figure ES-8 is due to the same reason mentioned earlier for dynamic simulators. From Figure ES-7, the trends of requirements in dynamic simulators to study future scenarios of grids include reduced time steps, increased number of states per unit that need to be simulated, and increased total number of states. These changes are needed because of the future grid scenarios and the high-fidelity models being considered (Section 3).



(a) Component Simulators



(b) EMT Simulators

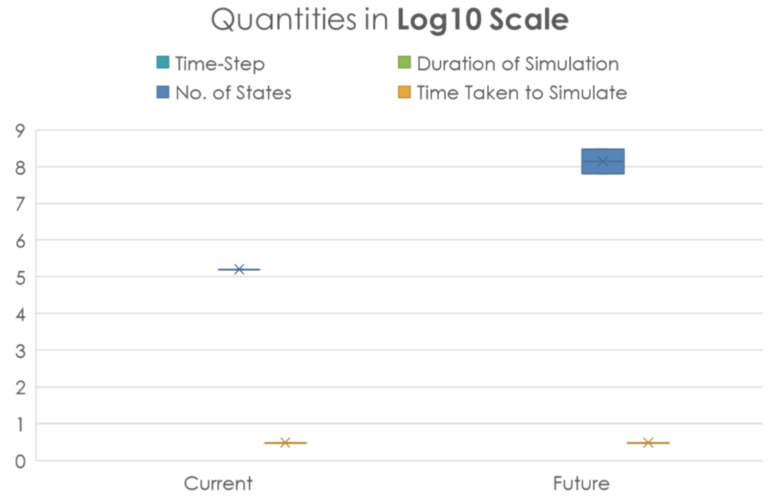


(c) TS Simulators

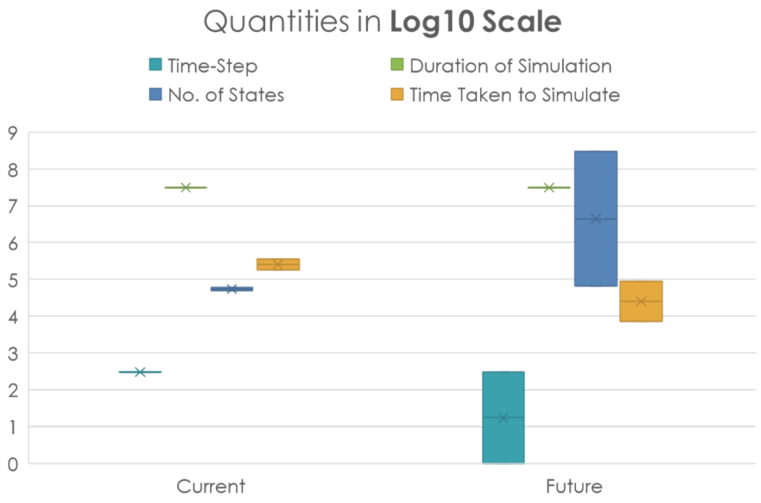
Figure ES-8. Characteristics of existing dynamic real-time simulators (Current) and the required characteristics in future dynamic real-time simulators (Future).

4.2 STEADY-STATE SIMULATOR CHARACTERISTICS

The characteristics of existing power flow simulators are shown in Figure ES-9 (Current). The requirements from the power flow simulators to study future scenarios of the grid are also shown in Figure ES-9 (Future). The range observed in Figure ES-9 results from the different percentage of transmission loads modeled using distribution system networks. The range considered varies from 5 to 10% of transmission loads in EI-ERCOT-WI interconnected grids. From Figure ES-9(a), the trends of requirements in power flow simulators to study future scenarios of grids include increased number of states. The corresponding trends observed in QSTS simulators are increased number of states and reduced time steps. These changes are needed because of the future grid scenarios and the high-fidelity models being considered (Section 3).



(a) Power Flow Simulators



(b) QSTS Simulators

Figure ES-9. Characteristics of existing steady-state simulators (Current) and the required characteristics in future steady-state simulators (Future).

The characteristics of existing QSTS real-time simulators are shown in Figure ES-10 (Current). The requirements from the QSTS real-time simulators to study future scenarios of the grid are also shown in Figure ES-10 (Future). The range observed in Figure ES-10 is due to the same reason mentioned earlier for steady-state simulators. From Figure ES-10, the trends observed in QSTS simulators are increased number of states and reduced time steps. These changes are needed because of the future grid scenarios and the high-fidelity models being considered (Section 3).

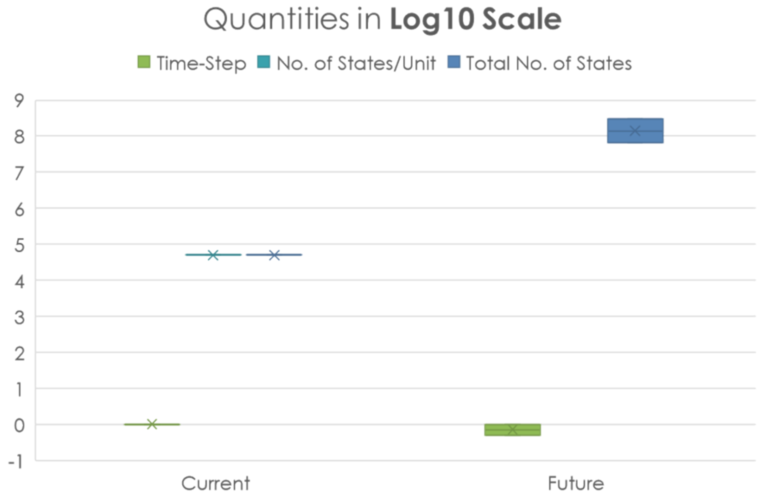
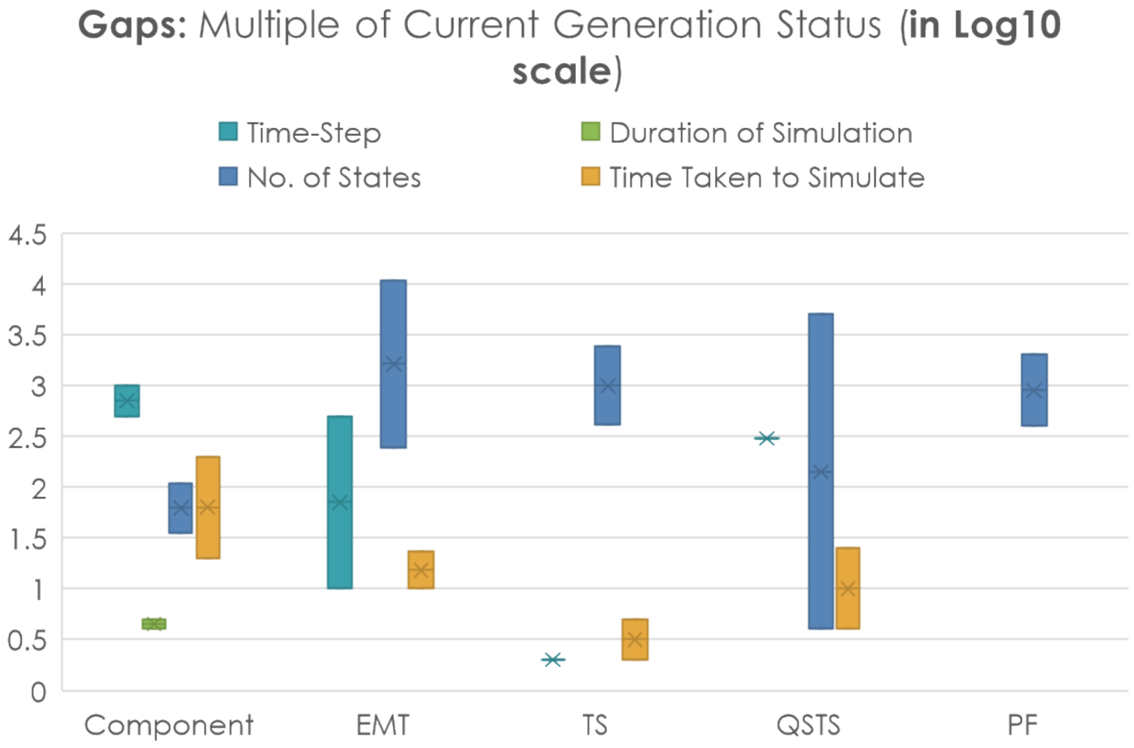


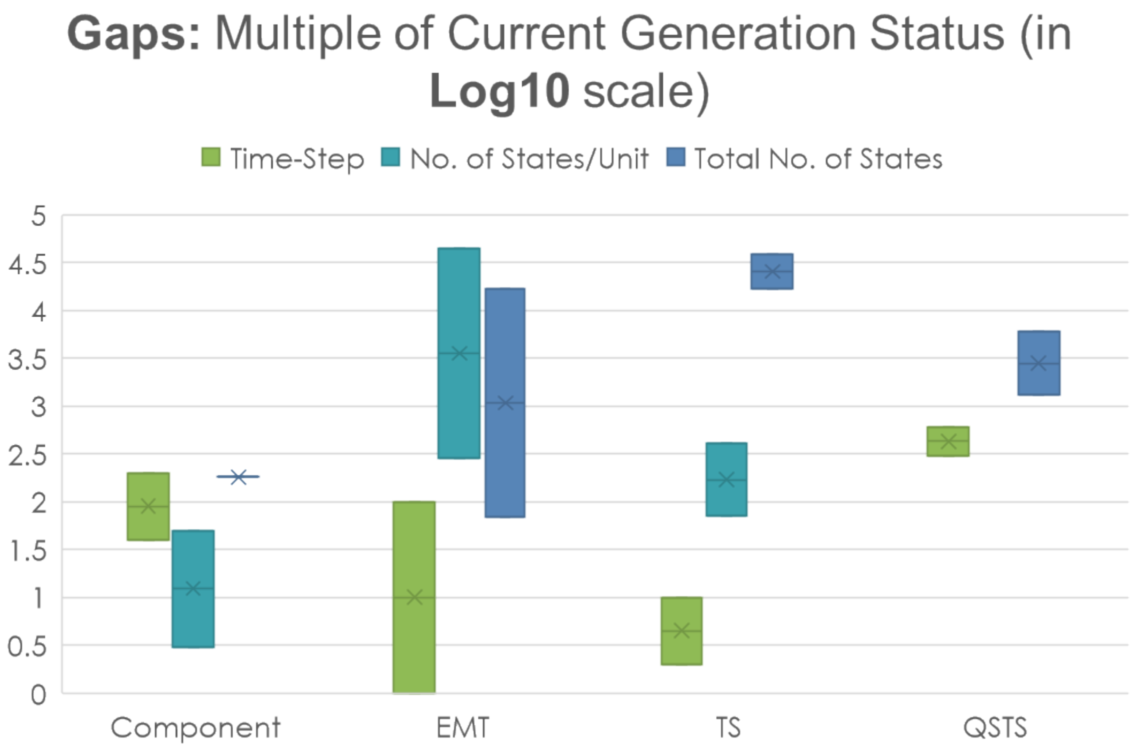
Figure ES-10. Characteristics of existing QSTS real-time simulators (Current) and the required characteristics in future QSTS real-time simulators (Future).

4.3 SUMMARY OF GAPS AND FINDINGS

From the characteristics identified in simulators and real-time simulators, the gaps identified in the simulators are summarized in Figure ES-11. The gaps in simulators identified include the requirement of decreased time-steps, increased number of states to be simulated, and decreased time taken to simulate. These gaps indicate the need for increased computing resources and efficient algorithms to simulate future scenarios of grids. The gaps in real-time simulators identified include the decreased time-steps, increased number of states per unit, and increased total number of states. These gaps indicate the need for research into computing architectures and algorithms that enable the real-time simulation of future scenarios of grids. Specific set of recommendations are providing in the next section.



(a) Simulators



(b) Real-time Simulators

Figure ES-11. Summary of gaps in simulators to simulate grids with high penetration of power electronics.

5. RESEARCH QUESTIONS AND RECOMMENDATIONS

Based on the gaps identified in Section 4 and the analysis performed in Sections 2 and 3, the following research questions were identified:

- How can simulation of large area EMT models be performed with more complex and faster acting power electronics in a reasonable time? The large area may result from simulation of transmission-distribution grids or larger transmission grids.
- What should be the boundaries of EMT and TS simulations for high penetration of power electronics?
- How can simulation of large-scale EMT-TS models be performed in reasonable time?
- How can multidomain simulations (e.g., Component-EMT-TS-QSTS) be performed in a reasonable time?
- How can convergence be achieved of ac-dc or T&D systems' power flow and QSTS algorithms with minimal iterations to solve in a reasonable timeframe?
- With the evolution of grid and computing upgrades, can the QSTS and power flow simulator's performance objectives be upgraded? For example, can one of the NERC requirements to perform contingency analysis in every 30 min be upgraded?

- When should QSTS simulations be performed? Which grids (e.g., transmission, subtransmission, distribution grids) need QSTS studies? What simulation parameters (e.g., time steps) are needed to perform these studies? Can these studies be standardized?

- What new computing architectures can be leveraged for large area high-fidelity dynamic real-time simulations?

- What algorithms can enable large number of multicore or GPU-based implementations of real-time simulations?

- What are the newer hardware architectures that can enable faster emulation capabilities?

- How can machine learning techniques be leveraged to improve the existing simulation capabilities?

In addition to the research questions identified above, the following set of recommendations are provided for dynamic simulators:

- *Recommendation 1*: Modeling improvements are needed in current generation of simulators. For example, grid-forming inverter models of hybrid PV-ESS, ESS, wind-PV, etc. are needed to be included in existing simulators. Standardizing links between different simulator domains (e.g., EMT-TS, EMT-Component, etc.) is needed.

- *Recommendation 2*: Several orders-of-magnitude improvement is needed in dynamic simulators (EMT, components) to enable planning and operation of future electric grids with high penetration of power electronics. The simulators include capability to cosimulate dynamics in different timescales (e.g., component, EMT, TS, QSTS) or T&D system dynamics. The simulations need to exploit the multithread/core capability of emerging computing solutions and be cost-effective. Potential solutions could be used for real-time DSA.

- *Recommendation 3*: Intelligence and enhanced automation capability needs to be embedded within simulators to provide the capability to simulate higher fidelity models in future electric grids within reasonable timeframes and with minimal human intervention.

- *Recommendation 4*: Adaptive simulators that switch between dynamic simulators, QSTS simulators, or a combination of both need to be developed. For example, in [78], adaptive simulator that switches between QSTS and TS simulators has been developed.

- *Recommendation 5*: Early-stage research is needed on algorithms and applied mathematics to simulate dynamics on new computing architectures (like quantum computing, neuromorphic computing) that may provide leap-of-faith benefits in simulating higher fidelity of component models and larger size of grids.

The following recommendations are provided for steady-state simulators:

- *Recommendation 6*: Power flow algorithms for ac-dc or T&D systems are needed in scenarios with increased dc systems and with high penetration of power electronics.

- *Recommendation 7*: High-performance computing (HPC) power flow algorithms are needed for faster convergence between studies. The HPC algorithms are needed for large-scale contingency analysis that includes multiple power flow runs and postprocessing. These algorithms need to meet the NERC requirement for contingency analysis based on real-time operating points every 30 min by transmission owners and reliability coordinators.

- *Recommendation 8*: New system strength metrics and short circuit calculation algorithms are needed for high penetration of power electronics. These algorithms would serve as the preliminary screening for further dynamic study needs.

- *Recommendation 9*: Modeling approaches and algorithms for accurately capturing and testing power electronics control functions (slow evolving control) in QSTS algorithms are needed for areas with high power electronics penetration. The functions include voltage control in ac and dc systems with variable generation. This formulation should enable capability to study local and interarea coordination of resources including renewables and energy storage. Large-scale QSTS simulation algorithms for studying regional grids and interconnections with high penetration of power electronics are needed. T&D system's QSTS simulation algorithms are needed with increased penetration of DERs. Standardization of studies performed with QSTS simulations are needed.

The following recommendations are provided for dynamic and steady-state real-time simulators:

- *Recommendation 10*: Research is needed on computing architectures and designs that enable real-time simulation of high-fidelity power electronics and EMT simulation of large grids.

- *Recommendation 11*: Research is needed on algorithms and applied mathematics that enable EMT simulations of large grids in real-time in new computing architectures and designs.

- *Recommendation 12*: Research is needed on algorithms and applied mathematics that enable cosimulations (EMT, TS) of grids over a long period in real-time in new computing architectures and designs. Evaluate the need for QSTS in future grids, especially for very large systems (e.g., T&D of EI, WI, ERCOT).

- *Recommendation 13*: Research is needed on high-bandwidth emulators (that includes an improvement by an order of at least 10) that can capture fast transients in the grid and power electronics without instability caused by the delay in the response of the current generation of emulators.

Final recommendations are provided here:

- *Recommendation 14*: Data collection from components (like plants) and structuring the data for information to be used by simulators is needed. Translation of data from one simulator to another needs to be standardized and considered.

- *Recommendation 15*: Model validation and verifications for next-generation high-fidelity component models is needed.

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APPENDIX A. GLOSSARY OF TERMS

1. ***Time steps*** is the incremental change in time for which the governing equations are solved
2. ***Duration of simulation*** is the virtual time for which the system needs to be simulated
3. ***No. of states or total no. of states*** is the states represented in the differential algebraic equations
4. ***Time taken to simulate*** is the actual time taken to simulate the system for a given duration of simulation and no. of states
5. ***No. of states/unit*** is the states simulated in a single computing unit that could be a central processing unit (CPU) or field programmable gated array (FPGA) or graphic processing unit (GPU)
6. ***Real-time simulation*** is the simulation of systems that require synchronization of time-steps with an external clock
7. ***Virtual/offline simulation*** is the simulation of systems without any synchronization requirements. The time taken to simulate a given duration of simulation will not be equal to the duration of simulation
8. ***Faster-than-real-time simulation*** is the simulation of systems that can be performed faster than the external clock. An example is the online stability assessment tools that require PF or TS or EMT simulations to be completed for several contingencies within defined time intervals (e.g., 1–30 min)