Smart Grid Simulations and Their Supporting Implementation Methods

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(Invited paper)

Abstract—In this tutorial we present state-of-the-art as well as new methods for simulating various planning, operation, stability, reliability, and economic models of electric power systems. The discussion is driven by both first-principle models and empirical models. First-principle models result from the fundamental physics and engineering that govern the behavior of various components of a grid. Empirical models, on the other hand, are models that result from statistics and data analysis. We overview a wide spectrum of applications starting from planning models with a time-scale of simulation in years to real-time models where the time-scale can be in the order of milliseconds. We present a list of simulation software that are popularly used by the power engineering research community across the world. The increasingly important roles of power electronics, communication and computing, model aggregation, hybrid simulation, faster-than-real-time simulation, and co-simulation in emulating the daily operation of a grid are enumerated. The importance of research testbeds for testing, verification and validation of complex grid models at various temporal and spatial scales is also highlighted. The overall goal is to provide a vision on how simulations and their supporting implementation methods can help us in understanding the evolving behavior of tomorrow’s power networks as a truly intelligent cyber-physical system.

Index Terms—Simulations, modeling, stability, planning, operations, power electronics, electric markets, cyber-physical systems

I. INTRODUCTION

Simulation is defined as the process of using a mathematical model to study the behavior and performance of a physical system. When it comes to understanding the behavior of an enormous, complex, multi-time-scale system such as an electric power system, simulations are the primary tool that one has to rely on. Accurate simulations can guide the operation, planning, and control of power systems at all levels - generation, transmission, distribution, customers and markets [1]-[3]. They are essential for analysis and evaluation of power system operations. They improve system planning and design. They help in recognizing and in mitigating potential hidden problems in the grid, avoid unforeseen errors, and prevent system interruption, and can determine under-utilization of system resources. They accelerate engineer and operator training, reduce design and commissioning time, and help power system operators in avoiding inadvertent plant outages caused by human error and equipment overload. Simulation is also one of the most effective ways to teach power engineering to undergraduate and graduate students.

Currently, power systems in different parts of the world are undergoing revolutionary changes in both architecture and operating principles [4]-[6]. The modern grid requires a tight integration of physical assets with cyber information to allow efficient transportation of data and control signals, and also to develop an open and real-time market. The envisioned digital grid of tomorrow must facilitate the open competition and innovation needed to accelerate the adoption of renewables while satisfying various challenges related to grid stability, markets, and dynamics. It must also allow for active participation of customers in day-to-day grid operations through data-driven programs such as demand response. None of these changes, however, can be implemented on the grid unless we have a reliable simulation capability. Simulations will be essential to understand all complex interactions between cyber, physical, and social layers of tomorrow’s grid.

Motivated by this challenge, in this paper we review a list of methods that are currently used as well as new methods that will potentially be used for simulating various planning, operation, stability, reliability, and economic models of power systems. We base our presentation on simulations of both physical models and heuristic data-based models. Physical models describe the behavior of physical components in the grid such as synchronous generators, induction motors, transmission lines, control equipment, loads, transformers, relays and circuit breakers. Heuristic models, on the other hand, are employed to describe uncertainties as well as the behavior of many other engineered and human-driven infrastructures underlying the grid [7], [8]. A list of simulation software is presented. New models arising from non-conventional generation sources and loads, with an emphasis on power electronics, are presented. The need for larger-scale simulations in order to transition from local monitoring to system-wide monitoring is highlighted, together with a discussion on how new methods of measurement-based model aggregation can help these wide-area simulations. The increasingly important roles of co-simulation, faster-than real-time simulations, predictive simulations, and the associated challenges in communication and computing on daily operation of the grid are also presented.

The rest of the paper is organized as follows. Section II reviews fundamental models for power system simulations. Section III summarizes the current approaches for simulation. Section IV presents the challenges in computational complexity, while Section V describes the impact of power electronics in conventional simulation models. Section VI describes the need for co-simulation of transmission and distribution system models. Section VII describes co-simulation of power grid with other critical infrastructures. Section VIII presents cyber-physical modeling challenges, while Section IX covers faster-than real-time simulations. Section X discusses the future of remote simulation testbeds. Section X concludes the paper.
II. SIMULATION MODELS AND APPLICATIONS

We start our discussion with a comprehensive list of applications that power engineers need to simulate for everyday operations of the grid. Many of these applications lead to optimization problems whose solutions decide the setpoints for decision variables that are needed to operate the grid in a stable, efficient, economic, and reliable way. These optimizations need to be executed over large number of variables while following different constraints arising from the physical behavior of the grid, thereby necessitating simulations. The following list captures the most important applications, but, of course, is not complete. We classify these applications with respect to their ‘time step’ of simulation as follows.

1) Steady-state simulations:
   - Power flow
   - State estimation
   - Steady-state security assessment
   - N-1, N-1-1 contingency analysis
   - Fault analysis, fault location analysis
   - Volt/VAR optimization
   - Symmetrical components and unbalanced faults
   - Induction motor analysis
   - Device coordination and selectivity
   - Reliability assessment
   - AMR/AMI integration
   - Power system markets
2) Long-term planning (in years)
   - Production costing
   - Model validation of generators
   - Reliability evaluation
3) Scheduling (in hours)
   - Economic dispatch
   - Optimal power flow (OPF)
   - Unit commitment
   - Hydro-thermal Coordination
   - Preventive Security Constrained OPF
   - Weather modeling and predictions
4) Slow dynamic simulations (in minutes)
   - Voltage stability
   - Loadability limit calculations
5) Electro-mechanical simulations (in seconds)
   - Automatic generation control (AGC)
   - Operator training simulator (OTS)
6) Fast electro-mechanical simulations (in milliseconds)
   - Modal analysis of oscillations
   - Oscillation damping control
   - PSS, FACTS controller tuning
   - Transient Stability
   - Synchronous machine transient analysis, including harmonics and unbalanced short-circuit faults
7) Electro-magnetic simulations (in microseconds)
   - Electro-magnetic transient program (EMTP)
   - Geomagnetic Induced Currents (GIC) calculations
   - Arc flash hazard analysis

Each of these applications come with their own first-principle physics-based models that enable their simulations. These models are mostly nonlinear, and described by a large set of algebraic and differential equations whose evolution vary over different time-scales as noted in the list itself. Most of these models exhibit complex nonlinearities such as saturation, deadband, if-then logic rules, and non-smooth behavior [9]-[11]. We start our discussion by recalling a selected set of models that represent the various fundamental building blocks of a power system. These models are often used for running simulations on academic examples of a grid, mostly at generation and transmission levels. Depending on the accuracy and resolution of the simulations that one may be interested in, these models by themselves can quickly become quite complicated. To avoid this difficulty, we limit this section to only the most basic mathematical equations that capture the main functionalities of the system, and point the reader to appropriate references for more details.

A. Synchronous Generator Models

Consider a power system network with $n$ synchronous generators. Synchronous generators are modeled by a combination of Gauss’ law, Newton’s second law of angular motion, Kirchhoff’s law, Ohm’s law, and Faraday’s law of electromagnetic induction. A suite of such models with varying levels of complexity can be found in [11]. A convenient model that is often used for transient stability analysis, small-signal oscillation analysis, as well as for design and simulation of generator control systems such as Automatic Voltage Regulators (AVR) and Power System Stabilizers (PSS) is the so-called flux-decay model. This model assumes that the time constants of the $d$- and $q$-axis flux are fast enough to neglect their dynamics, that the rotor frequency is around the normalized constant synchronous speed, and that the amortisseur effects are negligible. The dynamic circuit of this model is shown in Fig. 1. Using the phasor variables used in this figure, the model is described by the set of differential-algebraic equations [12].

![Fig. 1. Dynamic circuit model of a synchronous generator](image)

1) Differential Equations:

\[
\delta_i = \omega_i - \omega_s
\]
\[
M_i \dot{\omega}_i = P_{mi} - E'_{qi} I_{qi} - (x_{qi} - x'_d) I_{di} I_{qi}
- D_i (\omega_i - \omega_s)
\]
\[
T'_{dqi} \dot{E}_{qi} = - E'_{qi} - (x_{di} - x'_d) I_{di} + E_{fdi}
\]
\[
T_{Ai} \dot{E}_{fdi} = - E_{fdi} + K_{Ai} (V_{ref,i} - V_i)
\]

for $i = 1, \ldots, n$.

2) Stator Algebraic Equations: Applying Ohm’s law to the stator circuit shown in Fig. 1, and after a few
calculations one obtains the following pair of algebraic equations:

\[ V_i \sin(\delta_i - \theta_i) + r_{si} I_{di} - x_{qi} I_{qi} = 0 \]  
\[ E'_{qi} + V_i \sin(\delta_i - \theta_i) - r_{si} I_{qi} - x'_{di} I_{di} = 0, \]

for \( i = 1, \ldots, n \).

3) Network Equations: These equations couple the active and reactive power produced by the generator to the power flowing through the transmission lines, and the power consumed by the loads. They will be provided shortly in section IIC where we discuss transmission line models.

Here, \( i \) is the generator index, \( i = 1, \ldots, n \). Equations (1)-(2) are referred to as the swing equations, (3)-(4) as the excitation equations, and (5)-(6) as the stator current balance equations. As shown in Fig. 1, the terminal voltage at the \( i^{th} \) generator bus is denoted as \( V_i = V_i Z \theta_i \) where \( V_i \) is the magnitude (volts) and \( \theta_i \) is the phase (radians). The symbols \( \delta_i, \omega_s, E'_{qi}, E_{fdi} \) respectively denote the generator phase angle (radians), rotor velocity (rad/sec), the quadrature-axis internal emf (volts), and field excitation voltage (volts); \( \omega_s \) is the synchronous frequency, which is equal to 120\( \pi \) rad/sec for a 60-Hz power system such as the North American grid. \( M_i \) is the generator inertia (seconds), \( D_i \) is the generator damping, \( P_{mi} \) is the mechanical power input from the \( i^{th} \) turbine (Megawatt), \( T_{dol} \) and \( T_{Ai} \) are the excitation time constants (seconds); \( x_{di}, x'_{di}, \) and \( x_{qi} \) are the direct-axis salient reactance, direct-axis transient reactance, and quadrature-axis salient reactance (all in ohms), respectively. \( V_{ref,i} \) is the setpoint value for the terminal bus voltage (volts) of the generator, and \( K_{Ai} \) is a proportional controller that regulates the voltage \( V_i \) to this setpoint in steady-state. This controller is referred to as a Automatic Voltage Regulator (AVR). Additional control signals can also be added to the RHS of (4) through the field voltage \( E_{fdi} \). These controllers are referred to as Power System Stabilizers (PSS), which takes feedback from the generator speed, and passes it through a lead-lag controller for producing damping effects on the oscillations in the power flow after disturbances. More detailed description of the various parameters of this model can be found in [12], [5]. Besides the swing and excitation equations, the generator circuit model can have many additional state variables arising from AC and DC excitation, flux linkage, subtransient effects, washout filters, governor equations, automatic generator controllers (AGC), connections to other control devices such as FACTS and HVDC, and so on.

B. Models of Renewable Energy Sources

The modern day grid is seeing significant penetration of wind and solar power, both of which come with interfacing power electronic converters, Fig. 2 shows a schematic diagram on how these non-conventional distributed energy resources (DERs) are typically integrated with the main grid. We next summarize the state-space simulation models of these DERs to understand how their dynamic signal flows couple with the grid variables.

1) Wind Generator Models: A wind power system comprises of wind turbines, their associated control systems such as pitch and yaw controllers, doubly-fed induction generators (DFIG), and their associated internal voltage and current regulators. The turbine can be modeled by a single-mass or double-mass unit with gearboxes that couple its shaft with the rotating shaft of the DFIG. The turbine is driven by an aerodynamic torque, which is typically a cubic function of the wind velocity. The DFIG is modeled through the dynamics of its stator and rotor currents (Amperes), expressed in a rotating \( d-q \) reference frame. A linear model for the DFIG is often written as [13]

\[
\begin{pmatrix}
i & \dot{i} \\
E_w &= \gamma (v_{1q} i_{qs} + j v_{1d} i_{ds})
\end{pmatrix}.
\]

The linearization is generally done at the operating point that corresponds to the wind velocity that produces maximum wind power output in steady-state. A control scheme called maximum power-point tracking control (MPPT) is used to compute the setpoints for the DFIG currents corresponding to this maximum power. The variable \( \omega_g \) (rad/s) is the rotor angular velocity whose dynamics are decided by the turbine mechanics [13], and skipped here for brevity. The states \( i_{dr} \) and \( i_{qr} \) are the \( d \)- and \( q \)-axis rotor currents (Amps), \( i_{ds} \) and \( i_{qs} \) are the \( d \)- and \( q \)-axis stator currents (Amps), \( v_1 = [v_{1d} \ v_{1q}]^T \) is a column vector of the \( d \)- and \( q \)-axis stator voltage magnitudes (volts) at the bus where the wind power plant is connected to the grid, \( v_2 = [v_{2d} \ v_{2q}]^T \) represents the \( d \)- and \( q \)-axis rotor voltages (volts), and \( E_w = F_w + jQ_w \) is the total effective wind power injected into the grid. Explicit mathematical expressions of the matrices \( A, R \) and \( B \) can be found in [14]. The positive constant \( \gamma \) is the number of wind turbines in the plant, which when multiplied to the power output of each generator provides the total power output of the wind farm. Typically, both the \( d \)- and \( q \)-axis currents of the rotor need to be regulated to pre-computed setpoints based on MPPT. This is usually achieved by simple PI control.
The ability to control the mechanical torque of a wind turbine applied to the generator using pitch control, and electromagnetic torque using rotor current control enables a wind power system to avoid any mismatch between mechanical torque and electromagnetic torque, and therefore, to avoid any rotor deceleration under network frequency decline. Since inertia of a rotating machine is equivalent to the time constant of its frequency dynamics, this property of a wind power system is equivalent to having zero rotor inertia [16]. Thus, the wind power model (7) is often referred to as a low inertia model. The same holds for a solar cell, whose model does not involve any rotational dynamics [15]. Simulations of grid models integrated with these DERs thus often show very sharp declines in the grid frequency due to this low inertial effect. Several examples can be found in [17], [18]. Impact of this effect on electro-mechanical oscillations were shown via simulations in [19].

2) Converter Models: Three-phase pulse-width-modulated (PWM) converters are used for integrating DERs with the grid. Assuming a direct-quadrature synchronous reference frame, the converter model can be written as [20]

\[
\begin{align*}
L_{\alpha d} & = \omega_x L_{\alpha q} - \rho v_{\text{dc}} \\
L_{\beta q} & = -\omega_x L_{\beta d} + \rho v_{\text{dc}} \\
\dot{i}_{\text{dc}} & = \frac{e_q i_q}{v_{\text{dc}}} 
\end{align*}
\]

where \(i_d\) and \(i_q\) are the d- and q-axis currents (Amps) flowing into the converter, \(e_q\) is the q-axis voltage (volts) at the bus connecting to this converter, \(v_{\text{dc}}\) and \(\dot{i}_{\text{dc}}\) are the converted DC voltage (volts) and current (Amps), \(\rho\) is the duty cycle, and \(L\) is the filter-inductance (milli-Henry), and \(\omega_x\) is the synchronous frequency (rad/s). Generally, a PI controller is used to regulate the output DC current of the converter to a desired setpoint.

3) Storage models: Today’s power grid is also experiencing penetration of electrical battery storage at various scales. Typical models of batteries involve electro-chemical equations that reflect their internal physical principles, coupled with power flow balance that connect them to the grid. Many variants of battery models with different levels of complexity exist in the literature [21]. A simple model can be considered as [22]

\[
\dot{q} = \frac{i_d}{C}, \quad v_{\text{dc}} = g(q)
\]

where \(q\) is the state of charge, \(C\) is the capacity of the battery (microFarad), and \(g(q)\) is a monotonically increasing function such that \(g(q) > 0\) if \(q > 0\), following from the electrochemistry of the battery cell.

C. Transmission Line Models

The state variables of the DERs, converters, and storage models are coupled to those of the main grid via power balance across the transmission lines in the grid. A transmission line is modeled using series resistance, series inductance, shunt capacitance, and shunt conductance. A line is defined as a short-length line if its length is less than 50 miles. In this case, the capacitive effect is negligible, and only the resistance and inductive reactance are considered. Assuming balanced conditions, the line can be modeled by an equivalent circuit of a single phase with a resistance. If the line is between 50 miles and 150 miles long, it is considered to have a medium length. The single-phase equivalent circuit is modeled as a \(\pi\) or \(T\) circuit. The shunt capacitance is divided into two equal parts, each placed at the sending and receiving ends of the line. If the line is more than 150 miles long, then it is classified as a long-length line, whose model, unlike the lumped parameter models of the above two types, must consider parameters uniformly distributed along the line. Those models are described by partial differential equations. For a medium-length line, the power balance equations at any bus \(i\) can be written as [11]

\[
\begin{align*}
\sum_{k=1}^{m} V_i V_k (G_{ik} \cos(\theta_{ik}) + B_{ik} \sin(\theta_{ik})) - P_{G_i} + P_{L_i} &= 0 \\
\sum_{k=1}^{m} V_i V_k (G_{ik} \sin(\theta_{ik}) - B_{ik} \cos(\theta_{ik})) - Q_{G_i} + Q_{L_i} &= 0
\end{align*}
\]

where \(m\) is the total number of buses in the network, \(V_i\) and \(\theta_i\) are the voltage (volt) and phase angle (radian) of the \(i\)th bus, \(\theta_{ik} = \theta_i - \theta_k\), \(P_{G_i}\) and \(P_{L_i}\) are the active power (Megawatt) generated and demanded at bus \(i\), \(Q_{G_i}\) and \(Q_{L_i}\) are the reactive power (MegaVar) generated and demanded at bus \(i\), and \(G_{ik}\) and \(B_{ik}\) are the conductance and susceptance (mho) of the line joining buses \(i\) and \(k\). For example, for the flux-decay model (1)-(6), the network equations linking the generator state variables and the transmission line flows can be written accordingly as

\[
\begin{align*}
0 &= I_{d_1} V_i \sin(\delta_i - \theta_i) + I_{q_1} V_i \cos(\delta_i - \theta_i) + P_{L_i} \\
&\quad - \sum_{k=1}^{m} V_i V_k (G_{ik} \cos(\theta_{ik}) + B_{ik} \sin(\theta_{ik})) \\
0 &= I_{d_1} V_i \sin(\delta_i - \theta_i) - I_{q_1} V_i \sin(\delta_i - \theta_i) + Q_{L_i} \\
&\quad - \sum_{k=1}^{m} V_i V_k (G_{ik} \cos(\theta_{ik}) - B_{ik} \sin(\theta_{ik})).
\end{align*}
\]

for \(i = 1, \ldots, n\). Since one may write \(G_{ik} = Y_{ik} \cos(\alpha_{ik})\) and \(B_{ik} = Y_{ik} \sin(\alpha_{ik})\), where \(Y_{ik}\) and \(\alpha_{ik}\) are the magnitude and phase of the element \((i, k)\) in the admittance matrix, a more popular representation of (10)-(11) is often written as [12]

\[
\begin{align*}
0 &= I_{d_1} V_i \sin(\delta_i - \theta_i) + I_{q_1} V_i \cos(\delta_i - \theta_i) + P_{L_i} \\
&\quad - \sum_{k=1}^{m} V_i V_k Y_{ik} \cos(\theta_{ik} - \alpha_{ik}) \\
0 &= I_{d_1} V_i \sin(\delta_i - \theta_i) - I_{q_1} V_i \sin(\delta_i - \theta_i) + Q_{L_i} \\
&\quad - \sum_{k=1}^{m} V_i V_k Y_{ik} \sin(\theta_{ik} - \alpha_{ik}).
\end{align*}
\]

For non-generator buses, the network equations reduce to

\[
\begin{align*}
P_{L_i} - \sum_{k=1}^{m} V_i V_k Y_{ik} \cos(\theta_{ik} - \alpha_{ik}) &= 0 \\
Q_{L_i} - \sum_{k=1}^{m} V_i V_k Y_{ik} \sin(\theta_{ik} - \alpha_{ik}) &= 0.
\end{align*}
\]

If any bus \(i\) has a wind power generator, or a solar power generator, or battery storage connected to it, then the active
and reactive power generated (or consumed) by them will be added on the LHS of (14) and (15), respectively. Transmission line models also include transformers, circuit breakers, phase shifters, and shunt and series compensators.

D. Load Models

The active and reactive power drawn by the \( j \)th load can be modeled as [11]

\[
P_{Lj} = a_j V_j^2 + b_j V_j + c_j \quad (16)
\]

\[
Q_{Lj} = e_j V_j^2 + f_j V_j + g_j \quad (17)
\]

where, \( (a_j, b_j, c_j) \) and \( (e_j, f_j, g_j) \) are load-specific constant coefficients of appropriate dimension, \( V_j \) is the voltage magnitude at the load bus \( j \), and the three terms in each equation explicitly represent the contribution of each type of load, namely - constant impedance, constant current, and constant power load, respectively. Although constant impedance loads greatly simplify the derivation of the final state-space model of the entire power system network in an explicit closed-form, retaining this explicit form is not always possible for the two other types of loads. Thus engineers have to resort to software programs to numerically simulate the implicit model equations, linearize them over a given equilibrium point, and compute a small-signal state-space model. More complicated load models such as frequency-dependent loads have been developed by the IEEE task force in [23]. Several papers such as [24], [25] have also considered dynamic loads of the form

\[
T_p \frac{dP}{dt} + P = P_s(V) + k_p(V) \frac{dV}{dt} \quad (18)
\]

where, \( T_p \) is the load time constant, \( P_s(\cdot) \) is called the static load function, which is applicable in steady-state, and \( k_p \) is called the dynamic load function. In today’s grid operations especially, loads play an extremely important role by virtue of customer-side applications such as demand response. Recent papers such as [26], for example, have developed aggregated models for a population of air conditioning loads including statistical information of the load population, load heterogeneity, and their transient dynamics. Various other types of static and dynamic load models such as building loads and industrial machine loads can be found in [27], [28].

E. Models of Communication Systems

Power system operations today are becoming increasingly dependent on information and communication technology (ICT), thereby necessitating accurate modeling of communication networks. Communication is needed for mainly three classes of applications - namely, wide-area networks (WAN) used for wide-area control of transmission systems, local-area networks (LAN) used for smart metering, and home area networks (HAN) used for control of smart homes. Coming up with just one single representative mathematical model, however, is impossible, if not impractical. Researchers, therefore, often tend to couple actual communication systems with offline physical models of the grid, and emulate the interaction between the two in real-time, rather than using theoretical models. Examples include the Internet (or experimental variants of it such as Internet2) for long-distance data communication such as in wide-area monitoring and control of transmission networks, and wireless platforms such as Zigbee for short-range data communication such as in power distribution systems in university campuses and home automation. One important deciding factor behind the choice of these models is the communication delay that a message may experience while something critical is happening in the grid. For example, recent papers such as [29], [30] have used delay models arising in Internet-based wide-area communication networks for testing the efficacy of just-in-time wide-area control actions. Typically, these delays consist of three components:

1) the minimum deterministic delay, say denoted by \( m \),
2) the Internet traffic delay with Probability Density Function (PDF), say denoted by \( \phi_1 \), and
3) the router processing delay with PDF, say denoted by \( \phi_2 \).

The PDF of the total delay at any time \( t \) is written in terms of these three components as

\[
\phi(t) = \phi_2(t) + (1 - p) \int_0^t \phi_2(u) \phi_1(t - u) du, \quad t \geq 0. \quad (19)
\]

Here, \( p \) is the probability of the open-period of the path with no Internet traffic. The router processing delay is approximated by a Gaussian density function

\[
\phi_2(t) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}, \quad (20)
\]

where \( \mu > m \). The Internet traffic delay is modeled by an alternating renewal process with exponential closure period when the Internet traffic is on. The PDF of this delay is given by

\[
\phi_1(t) = \lambda e^{-\lambda t}, \quad (21)
\]

where \( \lambda^{-1} \) models the mean length of the closure period. The cumulative distribution function (CDF) of this delay model can then be derived as

\[
P(t) = \int_{-\infty}^t \phi(s) ds = \frac{1}{2} \left[ \text{erf}(\frac{t - \mu}{\sqrt{2\sigma}}) + \text{erf}(\frac{t - \mu}{\sqrt{2\sigma}}) \right] + \frac{(p - 1)}{2} e^{(\frac{1}{2} \lambda^2 \sigma^2 + \mu \lambda)} e^{-\lambda t} \left[ \text{erf}(\frac{\lambda^2 \sigma^2 + \mu}{\sqrt{2\sigma}}) + \text{erf}(\frac{t - \lambda^2 \sigma^2 - \mu}{\sqrt{2\sigma}}) \right]. \quad (22)
\]

Random numbers arising from this CDF were used in [29], [30] for simulating delays in a distributed communication network for wide-area monitoring and control [31], [32]. More details of these distributed networks will be presented in Section III when we describe the NASPNet.

The majority of the state-of-the-art communication models, however, are used for smaller-scale simulations that involve information exchange over a single channel. The challenge is to translate these single-path models to multi-path, multi-hop, shared network models where background traffic due to other parallelly running applications over shared resources may pose serious limitations in latencies. Recent references such as [33], [34] have provided interesting theoretical tools such as Markov jump process, Poisson process, multi-fractal models, and Gaussian fractional sum-difference models for modeling
delay, packet loss, queuing, routing, load balancing, and traffic patterns in such multi-channel communication networks.

III. CURRENT METHODS OF SIMULATIONS

We next discuss how simulations are currently handled by power system engineers and dispatchers. The discussion includes examples of several common software packages used for simulations in today’s grid, and also hardware-in-loop type simulations using real-time digital simulators (RTDS) and Opal-RT simulation facilities [35], [36]. List of currently used open-source software include UWPFLOW, TEFTS, MatPower, PST, InterPSS, GridLAB-D, OpenETran, OpenPMU, rapid61850, etc., while commercial software includes PowerWorld [37], PSS/E, PSLF, Aspen, E-Tap, PSCAD, Plecs, Open-DSS, Sim-Power Systems, and so on. Educational software programs include PSAT, which is based on Matlab/Simulink, and DOME, based on Python and public-domain C, C++, and Fortran libraries [38]. An excellent survey on open-source software can be found in [39]. The primary applications that these software are used for are as follows.

A. Power Flow Analysis

The power flow equations (12)-(15) can be expressed in a compact form as
\[
f(x) = 0 \tag{23}
\]
where
\[
f = \begin{bmatrix}
P_2(x) - P_{G2} + P_{D2} \\
P_3(x) - P_{G3} + P_{D3} \\
\vdots \\
P_m(x) - P_{Gm} + P_{Dm} \\
Q_2(x) - Q_{G2} + Q_{D2} \\
Q_3(x) - Q_{G3} + Q_{D3} \\
\vdots \\
Q_m(x) - Q_{Gm} + Q_{Dm}
\end{bmatrix}, \tag{24}
\]
\[x = \text{col}(V_1, V_2, \ldots, V_m, \theta_1, \theta_2, \ldots, \theta_m), \quad P_{Gi} \quad \text{and} \quad P_{Li} \]
are the active power generated and demanded at bus \(i\), \(Q_{Gi}\) and \(Q_{Li}\) are the reactive power generated and demanded at bus \(i, i = 1, \ldots, m\). In (23) we consider bus 1 to be the slack bus, and hence it’s power balance equation is not included in \(f(\cdot)\). Solution of these nonlinear equations is referred to as power flow. The majority of software packages these days come with their own sets of power flow solvers including accelerated Gauss-Seidel, Newton-Raphson, and perturbation-theory iterative techniques. Fast Decoupled and DC techniques are also often used [9]. The advantage of Newton-Raphson method is that it guarantees fast convergence as long as initial guess is close to the actual solution, and also that it enhances the region of convergence. The difficulty, however, is computing and inverting the Jacobian matrix \(J(x^k)\) at every iteration. Factorizing a full matrix is an order \(n^3\) operation, and hence extremely expensive. The order can be decreased, however, by exploiting the sparse structure of \(Y\), which induces sparsity in \(J\) as well. It has been shown through examples in [9] that by using sparse matrix methods results in a computational order of approximately \(n^{1.5}\), which can be a substantial saving when solving systems with tens of thousands of buses.

Power flow solution for distribution system models is done quite differently than in transmission models. Transmission systems have meshed networks, while distribution systems are mostly comprised of radial circuits. Software such as Distribution System Simulator (DSS) these days, however, can solve meshed distribution systems as well because they are intended to be used for distribution companies that may also have transmission or sub-transmission systems [40]. The circuit model employed can be either a full multiphase model or a simplified positive-sequence model. The power flow executes in numerous solution modes including the standard single snapshot mode, daily mode, duty-cycle mode, Monte Carlo mode, and several other modes where the load varies as a function of time. For planning purposes the simulation time period is chosen as a 24-hour day, a month, or a year.

B. Dynamic Simulations

Transient stability simulations for large power system models are based on the differential-algebraic (DAE) model (1)-(5) for synchronous generators, and the algebraic power flow equations (12)-(15). The DAE can be written as
\[
\frac{dx}{dy} = f(x, y, p), \quad x \in \mathbb{R}^n, \quad y \in \mathbb{R}^m, \quad p \in \mathbb{R}^p \tag{25}
\]
\[0 = g(x, y, p). \tag{26}
\]
The state vector \(x\) corresponds to the internal dynamic states of generators, exciters, governors, PSS, dynamic loads, power electronic devices, and so on. The output vector \(y\) contains the network power-flow variables e.g., bus voltage magnitudes and angles. The vector \(p\) describe machine parameters such as time-constants, inertia and damping, transmission line parameters such as line reactances and network topology, as well as operational parameters such as the status of shunt capacitor banks. The current trend in general-purpose DAE simulation, for example in Powerworld, PSCAD, and PSAT, follows hierarchical system modeling, which in addition to simplifying the conceptual and model-management tasks, also provides a good basis for incremental testing and validation of models and simulations. Traditional power system literature lists two broad modeling approaches for simulations - namely, explicit modeling and implicit modeling. Explicit models for dynamical systems use ordinary-differential equations (ODE) as the primary mathematical abstraction. The word ‘explicit’ here refers to causality, i.e., equations representing the physics of the system are written so that known quantities such as inputs and state variables are used to define unknown quantities. Languages associated with explicit modeling are block-oriented, such as Simulink and Ptolemy II [41]. Implicit models, on the other hand, directly use DAE as the primary mathematical abstraction. DAE based models emphasize the relationships between elements without regard to a particular causal ordering, and hence the name implicit. Example of such languages include Modelica [42], Hydra [43], and Sol [44].

C. Economic Dispatch and Optimal Power Flow

Linear and Quadratic programming techniques are the most common tools for both of these critical applications. Powerworld, for example, uses ‘Quadpro’ and ‘Rglpk’ packages
for optimal power flow (OPF), both of which are based on quadratic programming. A sparse solver for OPF using moment-based convex relaxation has been proposed in [45]. The classical OPF problem aims to minimize the function [9]

$$J = \sum_{i \in \mathcal{G}} (c_i P_{Gi}^2 + c_{i2} P_{Gi} + c_{i0}),$$

(27)

which is the sum of the quadratic costs accounting for the cost of active power generation at every generator bus (the set of all generator buses being denoted as $\mathcal{G}$) over the bus voltages, active and reactive power generations, subject to different system-level constraints. In general, this problem is non-convex, and difficult to solve. Recent results in [46], [47] have derived conditions on power system models that guarantee zero duality-gap so that semidefinite programming (SDP) can be used to retrieve the global optimum solution to the OPF problem. Sufficient conditions for global optimality have been presented in [48]. The results have been extended to meshed transmission network topologies in [49].

D. Fault Analysis

Fault simulation packages simulate single-phase and 3-phase bolted faults for interconnected power system models, and make provision for complex fault impedance. The $Y$-bus building algorithm is commonly implemented to construct the admittance matrix [50], followed by sparse matrix inverse computations. Several fast algorithms exist for this - for example, direct methods via LU factorization, Recursive Green’s Function (RGF) algorithm, and more advanced newer and faster methods such as Fast Inverse using Nested Dissection (FIND). A list of simulation tools for comprehensive fault analysis can be found in [51].

E. Load Frequency Control

Load variations in a power system cause drifts in frequency and voltage from their nominal values, resulting in loss of generation due to tripping of transmission lines. These drifts can be minimized, and kept within tolerable limits by load frequency control (LFC) [9], [11]. In LFC simulations users can change loads in selected areas in the grid, and proportional-integral (PI) control is automatically initiated based on the speed droop settings of the areas. The areas share the load by changing their generation levels based on their preset percentage contributions. With increasing penetration of renewable power LFC will be required to compensate for not only short-term fluctuations in frequency but also long-term fluctuations that are conventionally dealt with by economic dispatch. Recent papers such as [52] have proposed the use of storage as a solution to this problem. Enhancing LFC algorithms to compensate for uncertainties introduced by intermittent renewables is currently an ongoing area of active research.

F. Operator Training Simulator

The simulation engine for the Operator Training Simulator (OTS) has to simulate the behavior of the power system in real time so that the operator trainee gets the feel of a real power system [53], [54]. As mentioned before, such a simulation consists of solving differential equations (the dynamic part) as well as the algebraic equations (the steady-state part). To solve this in real time the dynamic part must be faster than real time so that the steady-state part has enough time for its solution. Since the operator usually observes the power system through SCADA, which updates every few seconds, a time step of one second for the simulation provides enough accuracy. Today, however, with the increasing availability of phasor measurements which update at 30 Hz or more, the OTS simulation needs to be done at much smaller time steps. New OTS implementations are appearing that use the transient stability formulation with around 10 ms time steps to be able to generate phasor measurements in real-time.

G. Reliability Modeling and Simulation

Reliability modeling refers to the failure and repair cycle of power system components. These are typically modeled by alternating renewal processes. One common method is the sequential Monte-Carlo simulation with stochastic point process modeling [55]. The application of probability models to the evaluation of generation reliability allows for the integration of different unit sizes and types, the effects of maintenance, the capacity of interconnections and other factors such as economic aspects. The commonly employed metrics for this purpose are called “loss of load probability” (LOLP), “loss of energy probability” (LOEP), and “frequency and duration (FAD). For detailed definitions of these metrics please see [56].

H. Simulation of Power Markets

Electricity markets are one of the major drivers and enablers for power system operation [57], [58]. Many commercial software such as Powerworld, GridLAB-D, and Power Systems Optimizer (PSO) with mixed-integer programming solvers such as GUROBI currently exist for simulating power markets. Several research institutions have also recently developed efficient market simulators. Examples include the AMES (Agent-based Modeling of Electricity Systems) wholesale power market testbed at Iowa State University, JASA (Java Auction Simulator API) developed by Ripple Software Ltd., a Python-based software called MiniPower developed in University of Washington, and several other market simulators created by Argonne National Lab. Detailed descriptions of these packages can be found at [59]. The main applications of a power market simulator include valuation of assets including both physical and financial contracts, transmission planning, policy analysis and market design, market surveillance, generation scheduling and trading support, risk analysis, modeling of demand response participation in markets and ancillary services, and reliability assessments [60]. The key components of a market simulator are as follows:

1) **Inputs**: demand forecasts, generation and transmission expansion, fuel prices, emission allowance prices

2) **Models**: loads, demand response, generation and transmission models including storage and variable generations, market rules

3) **Algorithms**: maintenance scheduling, contingency analysis, co-optimization of energy and ancillary services, topology control, mixed-integer programming
4) **Physical outputs**: generation and reserve schedules, power flow, fuel usage, emissions, load curtailments
5) **Financial outputs**: electricity prices, revenues, costs.

In a typical power market simulator the user represents power generation companies, submitting hourly generation bids into a virtual market. Simulated agents submit these bids. Bids are submitted for 24-hour periods (day-ahead market) and entered into the model. The total of all energy bids submitted by a player may not exceed the operational capability of on-line generating units that she owns. Bid block sizes are determined by the player as part of her bidding strategy. Bid prices for each unit must increase as a function of block number. The software is then run to determine market clearing prices, generation levels for all units, and profits and losses for each market participant. Before starting the simulation, each participant is provided with a set of “market rules” that have to be followed by each player. The objective of the simulation is for each player to maximize her profit by selling electricity into the market. The player with the highest profit wins the game. If no one makes money, the player with the lowest loss is declared the winner. Net profit is calculated based on energy sales in each hour, real-time market clearing prices, incremental production costs for each block of each generation unit, energy production of each block, operating costs, and fixed capital charges. Appropriate test systems such as the eight-zone ISO-New England system has also been developed to showcase the efficiency of these simulation methods [59]. Multi-objective optimization is applied to ensure the security of the market operations [61].

I. Simulation of Smart Grid Communications

Incorporating communication models in smart grid simulations is becoming imperative in the current state of art. Real-time digital simulators (RTDS), for example, can seamlessly employ communication protocols such as IEC 61850 for substation automation applications, DNP3 and IEC 60870-5-104 for SCADA system applications, and IEEE C37.118 for Synchrophasor applications. Comprehensive surveys of various such communication protocols for smart grids can be found in [62]-[63]. In this section we highlight three of these communication models. The first one is used for emulating wide-area communication of Synchrophasor data in transmission-level systems, the second one for smart metering in distribution-level systems, and the third for home automation.

1) **NASPI-net**: Wide-area monitoring and control of transmission grids require communication of large volumes of Synchrophasor measurements from substations spread across hundreds of miles. The time-scale associated with taking these control actions can be in fractions of seconds. Therefore, controlling latencies and data quality, and maintaining high reliability of communication are extremely important for these applications. The media used for WAN communications typically use longer-range, high-power radios or Ethernet IP-based solutions. Common options include microwave and 900 MHz radio solutions, as well as T1 lines, digital subscriber lines (DSL), broadband connections, fiber networks, and Ethernet radio. The North American Synchrophasor Initiative (NASPI) [?], which is a collaborative effort between the U.S. Department of Energy (DOE), the North American Electric Reliability Corporation (NERC), and various electric utilities, vendors, consultants, federal and private researchers and academics is currently developing an industrial grade, secure, standardized, distributed, and scalable data communications infrastructure called NASPI-net to support Synchrophasor applications in North America. NASPI-net is based on an IP Multicast subscription-based model. In this model the network routing elements are responsible for handling the subscription requests from potential PMU data receivers as well as the actual optimal path computation, optimization, and re-computation and rerouting when network failures happen. An excellent survey of NASPNet can be found in [64].

2) **AMI Communication**: Advanced metering infrastructure (AMI) communications is a central topic for distribution grids today. AMI communication is typically executed via local area networks (LAN) that provide two-way communication paths between the consumer’s and the utility’s smart meters. The two predominant technologies involved are power line carrier (PLC) signals transmitted over the utility’s distribution lines, and radio frequency (RF). PLCs use frequencies and modulation techniques that translate into a range of available speed and bandwidth options, including the 60 Hz power wave as well as superimposing high-bandwidth carrier signals of other frequencies onto the power line. They are more cost-effective in low-density areas such as rural and suburban service territories where feeders serving the smart meters tend to be lengthy. Similarly, RF solutions include technologies that use an assortment of frequencies, covering a range of distances over a variety of network topologies. These types of LAN communications can also be used for demand response, load-control, and distribution automation [65].

3) **Home Area Networks**: Home area networks (HAN) are used for communication between devices behind a smart meter inside a consumer’s home. This includes messages to present information via in-home displays, as well as messages that demand response devices can use for controlling key appliances to manage energy usage and capacity constraints. HAN is being conceptualized in response to mandates across the nation to improve energy efficiency, and educate and empower consumers. ZigBee is a common protocol that is used for HAN. ZigBee messages are transported via RF messaging protocols in unlicensed RF spectrum shared by Blacktooth and Wi-Fi for communication between devices inside a house [62].

Despite the wide usage of these models, a long list of challenges still exist for modeling and simulation of today’s rapidly evolving grid. These challenges need to be surpassed over the next decade through research and development to create robust, reliable, and cheap simulation platforms. The following sections list five of those primary challenges.

IV. CHALLENGE 1: ADVANCED MODELING METHODS

With millions of new devices penetrating the grid with every passing day, simulation models for tomorrow’s grid are bound to become much more complex than just a set of DAEs as in (25)-(26). All of these new devices, that come with their own share of nonlinearities, will impact
the dynamics, stability, and most importantly the seconds to tens-of-seconds-time-scale performance of the grid when critical disturbances hit. Developing simulation models that can capture such impacts in a scalable way is a serious challenge. Heat flow models in buildings, for example, are extremely high-dimensional, complex, and nonlinear, often modeled by partial differential equation models, for which strong knowledge of fluid dynamics is required in developing reliable simulations. The increasing use of modern power electronic devices in the distribution grid, for example, is making the grid models nonlinear, and often non-smooth due to switching actions. A study recently reported in [66], in fact, shows that power electronic converters can pose critical limits on the line currents and voltages beyond which the system experiences a Hopf bifurcation leading to sudden vanishing of feasible equilibria. Taking all of these factors into account, a set of relevant questions that naturally arise are as follows.

1) With significant integration of wind, solar, storage, and electric vehicles, how can we develop holistic models that capture the dynamic impact of all of these new energy sources and sinks on the conventional grid? How can we identify important coupling parameters that can reveal the possibility of weak operating points that may lead to transient instability and voltage collapse?

2) How can we develop robust numerical methods that will enable us to simulate these models in a scalable and modular fashion so that if tomorrow one more wind plant or solar plant or load is installed in the system then it would not take an enormous amount of computational effort to re-simulate the new model.

3) Most importantly, as highlighted in sections II-E and III-I, with many of the modern-day grid applications becoming increasingly dependent on communication of information across large geographical spans of the grid, how can we accurately simulate the cyber-physical interaction between the physical model of a grid and the models of its computation and communication layers? The behavior of a power system is driven by physical laws while the behavior of communication networks depend largely on random stochastic processes, logic functions, if-then rules, and human decision-making. Hybrid system simulations will become imperative to capture the continuous-time state transitions of the physical models, and their coupling with the discrete-event state transitions in the cyber layer. Although combining discrete-time and continuous-time behavior is not new, and has been around in the power system literature since the inception of digital controls [67], the challenge lies in accurate modeling of stochastic channels, variable routing delays, protocols for managing queuing delays, and so on, all of which are essential ingredients for modeling a cyber-physical system (CPS).

4) Similarly, how can we model and co-simulate complex interactions between power system models and models of other engineered infrastructures such as transportation and social networks?

The key factor for these types of scientific experimentation is modeling. To properly answer these questions one requires a holistic approach to modeling by, for example, developing simulation models that are not only easier to build, reuse, and validate, but also those that fundamentally characterize the environment in which they operate. We next list the challenges that currently stand in way of these advanced modeling methods.

A. Structural Properties

One of the desired properties of simulation models is structural dynamics. By definition, structural dynamics is the notion that one is not able to predetermined the number of structural configurations that a system may take on. The concept is not new to power systems. Contingencies, renewable integration, and interactions between prosumers are few obvious examples. Upon such events, the structural orientation of the system along with the underlying mathematics that model the physics of the system change in quantity, direction, etc. Another desired property is to capture the hybrid nature of the grid operating as a CPS, consisting of a combination of continuous-time (physical domain) and discrete-time (cyber domain) behaviors. Component interactions is the third required property. Models that inherently and implicitly capture the interaction between different components are critical for holistic simulation approaches, especially when there is more than one explicit representation for a given component. Another necessary property is component reflectivity [68]. Models that are closely reflective of its components help in promoting modularity, and lessen the burden of deriving causality when the consequences of the interactions are not known a-priori.

B. Scalability

One big challenge is to enable a real-time simulation capability for power system models such as (25)-(26) at extreme scales. Foundational work on taxonomy theory for modeling and analysis of DAE power models has been done in theory [69], but its translation to simulation models is still missing. Software such as Modelica and Hydra, for example, need to be exploited for modeling scalability through modularity, composition, correctness, implicit representations and structural dynamics. All of these abstractions then need to be brought under the umbrella of a common modeling language and the front end of a compiler, followed by a library and language-level abstractions that support the needs of experimentation.

Scalability is also an issue for controller designs. Conventional controllers such as Linear Quadratic Regulators (LQR) involve the computation of large matrix decompositions that can result in detrimental numerical inaccuracies without any guarantee of robustness. They also demand every node in the network to share its state information with every other node, resulting in an impractically large number of communication links. Traditionally, control theorists have addressed the problem of controlling large-dimensional systems by imposing structure on controllers. The trade-off, however, is that the resulting controllers are often agnostic of the natural coupling between the states, especially the coupling between the closed-loop states, as many of these couplings were forcibly
eliminated to facilitate the design itself. Ideas on aggregate control [70], glocal control [71], and hierarchical control [72] have recently been proposed to address this challenge. What designers are still lacking, however, is a tractable approach for constructing controllers that can be simulated and implemented at the scale of hundreds of thousand of buses. Model aggregation has been proposed as one possible solution for this problem [73], [74].

C. Model Validation

Another significant challenge is the validation of the models used in these simulations. This is particularly true for the dynamic models of the generators and their associated controls. After the large blackout in the US west coast in 1996, it became clear that the generator models used in the studies were not accurate enough. Since then the Western Electricity Coordinating Council (WECC) standard requires updating of the model parameters through standardized testing. Power systems in other parts of the world where stability is an issue have followed a similar approach. However, off-line testing is expensive and as PMUs have proliferated over the past decade, using PMU data during disturbances to update model parameters on-line have become more common [75]. Several challenges still stand on the way. For example, new technologies such as renewable generation sources and storage that require power-electronic grid interfaces have completely new types of dynamic models, as will be highlighted in Section V. Developing accurate modeling methods and devising procedures to validate these models are currently lagging behind.

D. Model Aggregation

Given the large size and extraordinary complexity of any realistic power system, deriving and simulating the dynamic model for an entire network becomes extremely challenging. Constructing approximate, aggregated, reduced-order models using simplifying assumptions, therefore, becomes almost imperative in practice. Papers such as [76] have defined aggregation methods for simulation time, for generation units, and for load demand units. The performance of the aggregated models is checked against detailed models including binary effects such as minimum down-time, minimum generation or demand side contracts. This is especially important for control designs such as model predictive control, where very large optimization problems need to be solved online. The optimization in these cases usually has to be simplified by using approximated power plant models, aggregating several assets to single units, and limiting controller foresight. The main question is whether fast generation units, curtailable renewable generation, demand-side management on the consumer side, and storage capacities are still correctly represented in the approximate models so that one can guarantee optimal operation of the grid.

Not just for reducing complexity of simulations, model aggregation may also be necessary if one is purposely interested in simulating only a certain part of the grid. Or, perhaps a certain phenomenon that happens only over a certain time-scale. For example, one may be interested in simulating only the low-frequency inter-area oscillations of a group of synchronous generators instead of the entire spectrum of their frequency response. Identifying coherent sub-groups among this group of generators, aggregating the sub-groups into an equivalent hypothetical generator, and analyzing the oscillation patterns of these equivalents become necessary in that situation. These days we often hear power system operators mentioning ‘Northern Washington’ oscillating against ‘Southern California’ in response to various disturbance events. The main question here is whether we can analytically construct dynamic models for these conceptual, aggregated generators representing Washington and California, which in reality are some hypothetical combinations of thousands of actual generators. One example for this motivating problem is the Pacific AC Intertie system in the US west coast, a five-machine dynamic equivalent mass-spring-damper model for which has been widely used in the literature [75], [77]. This model is shown in Figure 3. The main question is - how can we construct an explicit dynamic model for this conceptual figure, and that too preferably in real-time, using voltage, current or power flow signal measurements in order to establish a prototype for the inter-area dynamics of the entire interconnection?

Recently, several papers such as [78], [79] have addressed this question, and derived a series of results on PMU measurement-based model reduction that combines aggregation theory with system identification. Several open questions still exist, however. For example, once a baseline model is constructed, one must study how it can be updated at regular intervals using newer PMU data. Ideas from adaptive learning and decomposition theory [80] can be useful for that. How this updated model can be used to predict the slow frequencies and corresponding damping factors also needs to be formalized and validated via realistic simulations. Questions also exist on how the reduced-order model can predict the sensitivity of the power flow oscillations inside any area with respect to faults and wind power penetration in any other area. If answered correctly, utilities can exploit this information from simulations of the aggregated model, and evaluate their dynamic coupling with neighboring companies, leading to more efficient resource planning. Significant amount of work still needs to be done in formalizing how different failure scenarios in the actual full-order grid model can be translated to the aggregated model, what kind of advanced signal processing and filtering need to be applied to PMU data for accurate identification of the aggregated model parameters [81], and how controllers designed based on the aggregated model can be mapped back to the original system for implementation.

E. Challenges in Power Market Simulations

Three main challenges facing power market simulators today are

1) the curse of one-scenario-at-a-time, meaning that simulators today are not set up to generate, execute, and post-process multiple scenarios taken together,

2) lack of parallel processing, meaning that many of the optimization problems used for market emulation are easily parallelizable but the software are not well-designed to take advantage of that, and
3) turn-around times are unacceptably long due to lack of scalable algorithms.

Many simulators today rely on heuristic optimization, which can be replaced by more sophisticated non-convex methods for solving mixed-integer programming problems. For example, as pointed out in [82], simulation times can be significantly improved if traditional game-theoretic market models such as Nash-Cournot models and supply function equilibrium (SFE) models are replaced by faster models such as strategic production cost models (SPCM). This is especially useful for simulating real-time markets. Examples of these cost models for capital investments in transmission networks were recently highlighted in [83]. Market operators are currently in need for software that can handle significant increase in computational requirements, workflow management, real-time data processing, and data storage. The use of cloud computing by which users can create their own virtual hardware environments for managing a variety of market processes has recently been proposed in [60] as a solution to this problem. Market emulators such as pCloudAnalytics using Amazon Web Services are currently being developed. Cloud-based simulators, however, come with their own share of research challenges such as cyber security, data privacy, and usage tracking and accounting.

F. Load Forecasting

As pointed out in Section IIIH, accurate load forecasting is a key requirement for power market simulations. Current forecasting models are based on autoregressive models, Kalman filters, nonlinear least squares, and non-parametric regression [84]. But the increasing use of demand-side participation in power systems is going to make load forecasting much more challenging. We need data-driven functional models that relate the value of load demands with predictor variables such as setpoints for all the generation resources, setpoints for the duty cycles of power electronic converters that connect renewable generators to the grid, weather data such as temperature and humidity levels in a hot versus cold day, amount of PV generation and battery storage units that may be owned by the customers, and so on. Recent results in the machine learning literature provide us with some positive hope of creating accurate models by using nonlinear regression methods and reinforcement learning [85]. As pointed out correctly in [85], it is not easy for a human operator to judge if the decision of changing the load setpoint is correct or not. Operators are more used to handling these types of load changes with fixed logic and rules, and prefer models that are more transparent, where it is clear exactly which factors were used to make a particular prediction. Deep reinforcement learning can be a perfect choice for that. This is particularly important for microgrid simulations as their control algorithms are strongly dependent on the forecasted loads.

G. Smart Loads

One challenge from the perspective of load modeling is the emerging concept of smart loads. This is becoming especially important for simulation of microgrid models. For example, recently a new technology called “electric springs” (ES) was proposed in [86] to enable a demand-side control scheme at low cost, and in a way less intrusive to the consumer compared to other demand-side response technologies such as energy storage and on-off control of loads. ES is a class of power electronic devices, and can be ideally regarded as a current-controlled AC voltage source. Installed in series with other non-critical loads, ES and the non-critical load together act as a smart load whose power consumption can be boosted and reduced in a plug-and-play fashion, whenever needed. This smart load can then easily participate in system regulation. However, a comprehensive microgrid model showing how these smart loads and their associated control systems will interact with the various DER models developed in Section II, for example, is still missing. Some preliminary results have been presented in [87], triggering potential research ideas along this direction.

H. Handling Model Uncertainties

Models are always an approximation. For example, as mentioned in Section II A, the phasor-based model (1)–(4) for synchronous generators is well-suited for transient stability analysis, but it ignores electro-magnetic transient phenomena. Even the load model (16)–(17) can become a gross approximation depending on the desired fidelity of a simulation. It is referred to as a ZIP (constant impedance-current-power) model. It does not capture the delayed voltage recovery associated with induction motor loads in distribution systems. Thus, it may be completely invalid if one intends to simulate those types of loads. This is a daunting challenge for the modern grid, where load models are further complicated by new protocols such as demand response, direct load control, vehicle-to-grid integration, and various other factors by which load variations are shaped through customer participation. Using approximate models may not provide a very good representation of the reality in these scenarios. Modeling and accounting for uncertainties thus becomes imperative.
A number of approaches are currently used for assessing and reducing the impact of uncertainty in power system simulations - for example, trajectory sensitivity method, probabilistic collocation method (PCM), grazing, etc. Two excellent surveys for these three approaches can be found in [88], [89]. The state trajectory is expressed as a flow function $x(t) = \phi(t, \theta)$, where $\theta$ is a vector of the model parameters. The trajectories arising from a perturbation $\Delta \theta$ is approximated as [89]

$$x(t) = \phi(t, \theta + \Delta \theta) \approx \phi(t, \theta) + g(t, \theta) \Delta \theta \tag{28}$$

where $g(\cdot)$ is the trajectory sensitivity function. Since (28) is affine in $\Delta \theta$, parametric uncertainties can be easily mapped through to bounds around the nominal trajectory. If the sensitivity $g(\cdot)$ is large, then one may try to minimize the uncertainty by estimating the parameter values directly from measurements using nonlinear least squares, with the solution obtained via a Gauss-Newton process. PCM, on the other hand, uses Gaussian quadrature concepts to select appropriate points from the set of uncertain parameters to approximate the mapping between parameters and outputs of a simulation. Grazing is used to determine the smallest changes in parameters that would cause a discrete event such as a protection operation. These information can help in assessing whether the simulation model is robust to parametric uncertainties.

V. CHALLENGE 2: ROLE OF POWER ELECTRONICS

In Section II we introduced dynamic models of power electronic converter circuits needed for DER integration. Traditionally, the simulations of such converters are carried out independently of those for power systems. But with renewable penetration and significant intrusion of power electronic devices in distribution grids, these simulations are gradually becoming more inter-dependent, and must be combined at the right scale [90]. Two important examples of power electronics are:

1) FACTS (Flexible AC Transmission System), and
2) HVDC (High Voltage Direct Current).

Both can assist power system operators during a contingency by rescheduling power flows to avoid overloading of AC transmission lines [91], [92]. Depending on applications, both detailed switching models and simplified average models may be used for simulating FACTS and HVDC converters. For transient stability studies, for example, it is adequate to represent the converters by their average models in which the valve switchings are ignored using duty-cycle based switching functions or approximated phase-locked loop models, thereby ignoring the AC and DC harmonics [93]. For other applications such approximations may not be valid, and detailed switching models may have to be used. Simulation of switching models, however, can sometimes become problematic for a number of reasons. The converters operate by using switches to change the configuration of a network at frequencies up to several megahertz, and the time constants of the network are usually one or more orders or magnitude larger than the switching period. Each switching event is a discontinuity. Standard simulators can run for hundreds of switching cycles, creating problem for the simulation software that may not have an explicit mechanism for handling such discontinuities. This can result in long simulation times due to reduced integration timesteps in the neighborhood of the discontinuity, lack of convergence, and erroneous outputs [94]. With the advancement in programming languages in the late 1990s, modeling languages such as Dymola were proposed to resolve this problem by using object-oriented programming. Today, software such as PLECS, PSIM, PSPice, OpenModelica, PSCAD, VisSim, SABER, COMSOL, Matlab, and LTSpice are all widely used for large-scale converter simulations.

Another factor motivating the interest for accommodating power electronics in power system simulations is the envisioned replacement of conventional low-frequency magnetic transformers in near future by power-electronic transformers made out of the solid-state technology. These transformers consist of a front-end rectifier stage, which converts high voltage AC to high voltage DC, a dual-active bridge (DAB) stage, which converts high DC voltage to a low DC voltage to be used for DC distribution segment, and a voltage-source inverter, which converts low DC voltage to low single-phase AC voltage to be used for AC distribution segments. Since a typical microgrid may contain several hundreds of these converters, a common practice is to use averaged models instead of detailed models, especially for transient stability studies. These models are most often described by nonlinear dynamics that are valid only in specified ‘safe zones of operation’ [66]. This is similar to the concept of reachable zones in DFIG-based wind turbine models, which are often used for testing their voltage ride-through capabilities [95]. High-fidelity simulations are required for revealing these safe zones for different operating conditions and network topologies.

A solid-state transformer (SST) contains both AC and DC terminals that may be connected to wind, solar, battery storage, and loads. Fig. 4(a) shows the interface circuit for AC components. A boost converter is coupled with the rectifier circuit to convert the lower DC voltage of solar generators to lower AC voltage. Fig. 4(b) shows the interface circuit for DC components. PV panels are directly connected with a boost converter to amplify the panel voltage to the DC bus voltage. Based on voltage level of the panels, other DC-DC converters can also be used for this interface. A similar interface with bi-directional energy flow can be used to control the battery charging and discharging for power and energy management of the system. The charging voltage of a battery is typically lower than the DC bus voltage. Thus, a good choice for this interface circuit is a buck converter for the DC energy cell, and an inverter-coupled buck converter for the AC energy cell. However, to allow flexibility in choosing the voltage rating of the battery, a bidirectional buck-boost converter is used for DC batteries, and an inverter coupled with a buck-boost converter is used for AC batteries. The circuits for AC and DC energy storage are shown in Fig. 5(a) and Fig. 5(b), respectively.

Recent examples in [66] show that when these circuits are connected to a radial distribution grid, the small-signal model of the system exhibits a wide variation in time-scales ranging from micro-second dynamics arising from switching to tens of seconds of dynamics arising from the inertial effects of the DFIGs. Thus, multi-time-scale numerical methods that can
successfully capture such large spectra of eigenvalues need to be developed as more of these power electronic devices get integrated to the grid.

\[ I_{\text{mpp}} \]

Boost Converter

\[ S_1 \]

Rectifier

(a) Boost converter and rectifier for solar AC interface

\[ I_{\text{mpp}} \]

(b) Boost converter for solar DC interface

Fig. 4. Power electronic converter models for renewable generators

\[ \theta(\dot{t}) = \omega_s t. \] (31)

Depending on more complex dynamic models of the PLL, \( \theta(t) \) may be simulated by more complicated functions than just a simple straight line. The important point to note is that although \( \theta(t) \) by itself is an unbounded function, it enters the rectifier dynamics through bounded trigonometric functions. The implications of these bounded time-varying terms for judging the stability of the converter models must be validated using simulations.

VI. CHALLENGE 3: CO-SIMULATION

A. Co-simulation of T&D Models

Traditionally, transmission and distribution grid models have always been treated as two individual, decoupled infrastructures. However, given the recent nationwide initiatives in promoting demand response (DR), many researchers are now proposing to bring these two infrastructures together, and co-simulate their models. Recent papers such as [85] have proposed so-called DR-advisors that act as a recommender for power consumption prediction and control strategies for the loads on both transmission and distribution sides of the grid. Necessary aggregation techniques may need to be applied here to lump the transmission grid as a single source of information, as shown in Fig. 6. Once a load is predicted and the DR strategy is evaluated, co-simulation models can guide operators on how to update the load setpoints. Highly reliable load forecasting, as mentioned earlier in Section IVF, will be critical for this purpose. Online estimation algorithms need to be applied for gathering adequate information about weather, possibilities of natural disasters, approximate generation schedules over the next hour, information about transmission line faults that may severely disrupt the currents flowing on the distribution side, and so on. The control algorithms for regulating the loads will thereafter need to be tuned accordingly, depending on whether the distribution grid can depend on the transmission grid for any deficit power feed.

B. Co-Simulation of Infrastructures

Not just for T&D models, co-simulation is being envisioned as a necessary tool for verification and validation of various other infrastructures whose functionalities are interconnected with power systems [63]. For example, power systems depend on the delivery of fuels to the generation stations through transportation services. The production of those fuels depends in turn on the use of electrical power. The fuels are also needed by the transportation services. Evaluating these types of interdependencies is critical when big natural calamities hit the grid, causing loss of power for extensive periods of time. Fig. 7, reproduced from [96], shows a logical diagram on how the power grid is dependent on seven other major infrastructures, and vice versa. This inter-dependence is only going to increase over time, thereby necessitating the development of modeling and simulation tools that can assess the risks and possible impacts of critical events on quality of life by identifying factors that trigger the domino effect between these eight infrastructures. Co-simulation can be a potential solution for this problem. Co-simulation refers to a combination of theory and techniques to enable global simulation of a coupled system via the composition of smaller simulators. Each simulator is a black-box mock-up of a constituent infrastructure, whose model is developed by its respective operator, allowing for
each operator to work on his part of the problem with his own domain-specific tools. An alternative to co-simulation is co-modelling, where models of the different infrastructures must be described in a unified language, and then simulated. There are advantages to this approach, but each domain has its own particularities when it comes to simulation as a result of which it is impractical to find a unified language that fits all. An excellent survey on this topic was recently presented in [97].

A recent study was done by Sandia National Laboratory in [98] about shock propagation and physical-to-market feedback in the US natural gas infrastructure using agent-based modeling and state-space dynamic models. A related study on co-simulation was done in [99] using the idea of co-optimization. Co-optimization models are computer-aided decision-support tools that search among possible combinations of different infrastructure-level investments to identify integrated solutions that are best in terms of cost or other objectives while satisfying all physical, economic, environmental, and policy constraints. Recent works in [99], [100] have reviewed the state-of-the-art in power system expansion planning tools including existing co-optimization models, and also summarized data and computational requirements for simulating co-optimization models. The conclusion was that co-optimization based modeling and simulations can be excellent tools for system expansion planning, and especially important for power systems given the large transmission investments that are anticipated to promote inter-regional power trades and renewable integration.

A typical co-simulation may consist of one or more of the following topics [97]:

1) Numerical analysis where conditioning, accuracy and stability of the coupled system model must be addressed.

2) Differential-algebraic system simulation: the compositions of co-simulation units are made through the algebraic constraints, similar to the power system model (25)-(26).

3) Hybrid systems: Co-simulation scenarios, generally speaking, involve hybrid systems where both continuous-time state transitions and discrete-event switchings are involved.

4) Hierarchy: Interconnected models of infrastructures are often hierarchical, and thus their co-simulation scenarios must be hierarchical too. Compositionality properties of co-simulations are, therefore, important research challenges.

5) Formal verification: Co-simulation orchestrators must be equipped with proper formal verification methods to coordinate the information flows between different computers running models of different infrastructures.

6) Structure and time-scales: Different infrastructures may have different structural properties in their dynamics, and different time constants, all of which are reflected in their co-simulations.

7) Time-varying models: Many subsystems, including power systems, can also have different models at different levels of abstractions while the same simulation is running. The relationships between these models must be known so that correct switching between the levels
of abstraction can be made at the correct time instants.

Co-simulations can facilitate fast automated decision-making for grid operators during emergency conditions. Significant amount of research still needs to be done, for example, on developing efficient algorithms for discrete-event based co-simulation models, their compositional convergence, hybrid co-simulations, identification and handling of discontinuities, real-time constraints, and the necessary simulation standards [97].

VII. CHALLENGE 4: CYBER-PHYSICAL MODELING AND SIMULATIONS

As mentioned in Section IIIE, power system operations today are becoming increasingly dependent on communication. New types of generation, loads and control devices are being added to the grid, adding more complexity to its dynamics, and therefore necessitating the traditional practice of local monitoring and control to be replaced by global or system-wide actions [31]. These actions require a robust and resilient communication backbone over which large volumes of grid data can be transported in real-time. Developing simulation packages for testing and validation of these communication networks, and the way they interact with the physical operation of the grid is currently a big challenge. Challenges in modeling and simulation on the communication plane, for example, can arise from modeling of delays, queuing, packet loss, routing, bandwidth sharing, and load balancing. Other important challenges can arise from inter-operability standards, interfacing middleware, security and privacy constraints. Typically, the Internet cannot provide the required latency and packet loss performance for grid operation under high data-rates. Moreover, the network performance is highly random, and therefore, difficult to model accurately. Very little studies have been conducted to leverage emerging IT technologies such as cloud computing, software-defined networking (SDN), and network function virtualization (NFV), to accelerate this development [101], [102]. With the recent revolution in networking technology, these new communication mechanisms can open up several degrees of freedom in programmability and virtualization for simulation platforms. However, customized SDN control and protocols, and sufficient experimental validation using realistic testbeds are still missing in almost all power system applications and in their hardware-in-loop simulations.

Fig. 8 shows a cyber-physical architecture that can bridge this gap. This architecture, proposed in [32], reflects the three pillars or the three C’s of any typical cyber-physical system, namely, communication, computing, and control. One may use SDN to model communication, cloud computing for computation, and distributed nonlinear control designs for control. The figure shows the example of a transmission network representing the physical layer, but the same architecture can very well be applied to distribution systems as well. The power system model, which may be running in RTDS or Opal-RT, is divided into multiple non-overlapping areas that represent balancing regions belonging to different utility companies. Time-synchronized PMU measurements from local buses inside each area are communicated to phasor data concentrators (PDCs), and then to virtual computers residing in a local cloud. The virtual computers are denoted as VM (virtual machine) in Fig. 8. The geographical location of the VMs can be close to that of the generators in that area so that the latency from PDC to cloud communication is small. The local clouds themselves constitute an Internet of clouds that connects the VMs through an advanced, secure, third-party wide-area communication network such as SDN. Virtual machines in each local cloud communicate with their neighboring machines inside the cloud as well as to those across other clouds exchanging PMU data, and computing control signals via pre-embedded feedback control laws. The control signals are, thereafter, transmitted back from the local cloud to the actuators of the corresponding generator models in RTDS or Opal-RT.

Cloud-in-the-loop CPS architectures can also be useful for emulating SCADA. Recent research trends indicate that in near future control centers will require hybrid software-hardware simulation platforms for SCADA and contingency analysis. One example is the Graphic Contingency Analysis (GCA) Tool developed in Pacific Northwest National Laboratory (PNNL) to provide effective decision making support to operators [103]. A SCADA-based state estimation (SE) simulator has been developed recently at Washington State University using the GridSim simulation platform [104]. More advanced SCADA emulators based on Synchrophasor data need to be
developed in the future. These emulators will require a very robust CPS platform such as the one shown in Fig. 8 for processing data at the substation level, fast communication of the results to the control center, and synchronization of the data at the control center in order to generate state estimates for an entire power system model. In Section II we highlighted the mathematical equations for such physical models. In the following subsections we discuss the modeling challenges for the cyber layer, which in this case is comprised of multitudes of virtual machines dispersed across the internet of clouds.

A. Simulation of Cyber Layer

Data delivery latency and loss rate are important factors in the performance of wide-area control and protection applications in transmission networks. Software such as RTDMS (real-time dynamics monitoring system), PGDA (phasor grid data analyzer), and GridSim are used for online oscillation monitoring using Synchronphasors. A list of related open-source software can be found in [105]. These simulation engines need to be integrated into executable actions so that results from the monitoring algorithms can be exported to a custom SQL database that can be set to trigger alerts or alarms whenever damping levels of oscillatory modes fall below pre-specified thresholds. These alarm signals need to be communicated to the operator through a reliable communication network so that the operator can take manual actions to bring the damping back to acceptable levels [106]. In recent years, simulation platforms such as ExoGENI-WAMS [107] have been developed to emulate such communication platforms. The computation and communication planes are entirely shifted away from the physical infrastructure, as shown in Fig. 8. The idea is similar to the NASPInet described in Section III, but with an additional layer of cloud computing. Service-based third-party private clouds are used to create on-the-fly virtual machines, which continuously receive real-time streaming data from specific sets of PMUs, and exchange them with both intra-cloud and inter-cloud VMs through a wide-area network such as Internet2. The measurements are digitally represented as a periodic stream of data points. The data delivery infrastructure for supporting these types of applications is still evolving. Another example of a CPS simulator is GridSim [108]. The data delivery component in this simulation platform, also referred to as GridStat, is a publish-subscribe middleware, which allows for encrypted multicast delivery of data. GridStat is designed to meet the requirements of emerging control and protection applications that require data delivery latencies on the order of 10 to 20 ms over hundreds of miles with extremely high availability.

Similar to GridStat, the VMs in any cloud-in-the-loop CPS simulator may consist of two communication planes, namely a data plane and a management plane. The data plane is a collection of forwarding engines (FEs) designed to quickly route received messages on to the next VMs. The FEs are entirely dedicated to delivering messages from publishers to subscribers. Routing configuration information is delivered to the FEs from the management plane. The forwarding latency through an FE implemented in software is generally on the order of 100 micro-seconds, and with network processor hardware it is less than 10 micro-seconds. The management plane, on the other hand, is a set of controllers, called QoS brokers, that manage the FEs of the data plane for every VM. The Quality-of-Service (QoS) brokers can be organized in a hierarchy to reflect the natural hierarchy in the physical infrastructure of the grid model. When a subscriber wishes to receive data from a publisher, it communicates with a QoS broker that designs a route for the data, and delivers the routing information to the relevant FEs and VMs, creating the subscription.

Simulation platforms such as GridStat are just starting points for research. Much more advanced cyber emulators need to be developed for the future grid. One outstanding challenge is to develop a reliable communication software that will enable timely delivery, high reliability and secure networking for these emulators. This is needed for all applications, whether that be on the transmission side or distribution side. Timeliness of message requires guaranteed upper bounds on end-to-end latencies of packets. Legacy networking devices do not provide such guarantees, neither for commodity Internet connections nor for contemporary proprietary IP-based networks that power providers may operate on. Moreover, direct communication lacks re-routing capabilities under real-time constraints, and resorts to historic data when communication links fail. Both timeliness and link-failures can be handled using the idea of Distributed Hash Tables (DHT), which was recently introduced for wide-area control applications in [109].

B. Simulation of Cyber Vulnerabilities

Another driving motivation for developing CPS-centric simulation tools for power systems is cyber-security [110], [111]. The integration of cyber components with the physical grid introduces new entry points for malicious attackers. These points are remotely accessible at relatively low risks to attackers compared to physical intrusions or attacks on substations. They can be used to mount coordinated attacks to cause severe damages to the grid. Attacks can be originated on the cyber layer as well to trigger cascading events leading to damages on physical facilities, leading to major outages. While simulation models have been developed to model electrical faults and device failures, we still do not have any reliable simulation package that can guide us on how the modern-day grid can be equipped with necessary protections against different types of cyber vulnerabilities. Several universities and national laboratories have started developing simulation testbeds to emulate these vulnerability scenarios. Research demonstration events such as Cyber Security Awareness Month, which is a student-run cyber security event in the US, has been introduced by the Department of Homeland Security [112]. The goal is for power system operators to work with these standards organizations to develop simulation software that can model, detect, localize, and mitigate cyber vulnerabilities in the grid as quickly as possible.

We conclude this section by showing a simulation of a denial-of-service (DoS) cyber-attack on a wide-area controller for the IEEE 39-bus power system. The details of this controller were recently reported in [113]. First, the power system model was linearized about the solution of its load flow. Then,
a linear quadratic regulator (LQR)-type optimal controller was designed, and sparsified using matrix sparsification methods. The control problem was stated as:

\[ \min_{K} J = \frac{1}{2} \int_{0}^{\infty} (x^T Q x + u^T R u) dt \]  
\[ \text{s.t., } \dot{x} = Ax + Bu \]  
\[ u = Kx, \ K = K(G), \ Q > 0, \ R \geq 0 \]  

where, \( G \) is a designated sparse graph topology imparted on the wide-area communication network. The nonlinear model of the power system was simulated with this sparse state-feedback controller using Power System Toolbox (PST) in Matlab [114]. A fault was induced at \( t = 0 \), and the small-signal speed deviations of the synchronous generators were recorded, as shown in Fig. 9. The closed-loop system behavior is observed to be stable. At \( t = 10 \) seconds, a DoS attack induced on the communication link connecting generators 1 and 8, which means that these two generators are no longer capable of exchanging state information for their control actions. Instability is noticed immediately, with the frequency swings diverging with increasing amplitude at a frequency of roughly 0.05 Hz. This can be seen in Fig. 9 onwards from \( t = 10 \) sec. At \( t = 60 \) sec, the communication links connecting generators (2, 6) and (3, 6) are added, and the corresponding control gains are recomputed. The system is seen to regain stability, indicating that the attack has been successfully mitigated. The frequency deviations are all seen to converge to zero over time.

The above example shows the importance of simulations for investigating different types of attack scenarios in the grid. Simulations can reveal the most important pairs of generators that must communicate to maintain stable operating condition before and after an attack, and also the lesser important pairs that, either due to large geographical separation or weak dynamic coupling, do not necessarily add any significant contribution to stability. Simulation packages also need to be developed for illustrating various other types of attack scenarios such as data manipulation attacks, jamming, eavesdropping, and GPS spoofing [115].

VIII. CHALLENGE 5: TECHNOLOGIES OF SIMULATIONS

A. Parallel Computing

An obvious approach to speed up simulations is to utilize parallel or distributed computing. Although specially written programs for particular parallel architectures can provide high speed-ups, the rapidly changing hardware and software makes it impossible to keep modifying the simulation programs to keep up. The trend today is to use multiprocessor computers with compilers that can distribute the computation optimally to multiple processors. For power system simulations, some applications are much more amenable to parallelization than others. For example, any simulation that requires running many contingencies (such as security constrained OPF) can run these hundreds of contingency cases in separate processes. The dynamics of individual generators can be run in parallel but the network that connects the generators has to be solved simultaneously. It turns out, however, that the algebraic equations representing the network cannot be parallelized very efficiently, and becomes the main bottleneck for speeding up power system simulations. Parallel computing can also be used for gain-scheduling of robust controllers.

B. Hybrid Simulations

In order to implement fast control strategies in grid models, it is highly desirable to have a faster than real-time emulation or simulation of that model in hand. One promising solution is hybrid mixed-signal hardware emulation. In these emulations, hardware-based digital simulation and analog simulation can be used in an integrative way to achieve a massively parallel and scale-insensitive emulation architecture. There have been several attempts at building hardware accelerators in the past [116], [117]. For example, the DAEs (25)-(26) can be emulated in hardware by a coupled set of oscillators, resistors, capacitors and active inductors. A higher frequency can be used so as to suit the scale of on-chip elements and permit faster than
real-time operation. These elements then need to be built on chip, and connected with a customizable switch matrix, allowing a large portion of the grid to be modeled in real-time. Researchers have proposed the use of Verilog-AMS model, which is a hardware modeling language that includes features for Analog and Mixed Signal (AMS) elements [118]. It can incorporate equations to model analog sub-components. The AMS model can be designed to emulate open-loop models of very large-scale power systems with tens of thousands of buses with built-in equations for AC power flow, electro-magnetic and electro-mechanical dynamics of synchronous generators and induction generators, AC load models, voltage control, droop control, automatic generation control (AGC), and power system stabilizers. Several challenges that still stand on the way for developing at-scale faster than real-time simulations are:

1) How to synthesize the transmission network without unnecessary and unrealistic assumptions, and approximations using state-of-the-art microelectronics design technology
2) How to develop a scalable mixed-signal emulation architecture capable of large power systems with tens of thousands nodes
3) How to design configurable units of emulation on a chip so that any large power system with realistic transmission connections can be realized via software-based configuration.

Research activities are underway on building VLSI chips that can scale to large grid models for faster than real-time emulators, especially directed towards transient AC simulations. In [117], for example, predictive simulations were shown to be very useful for real-time path rating. The concept was verified using a 39-bus power system model, shown in Fig. 10(a). To calculate the total transfer capability of Path 1, the generation level in Area I was increased while the generation in Area II was decreased progressively while screening contingencies. Comprehensive path rating studies considering N-1 contingencies were conducted using DSA Tools, developed by Powertech Labs. Simulation results, shown in Fig. 10(b), reflect that the total transfer capability can vary significantly in real time. The path rating estimated with the worst-case scenario would be the smallest of all values for 24 operating hours. Any capacity above the smallest number is an additional gain enabled by real-time path rating studies. If the additional transfer capability can be fully utilized, a total amount of 25.74% more energy can be transferred without compromising the current reliability level. This could generate multi-million dollar revenues.

IX. SIMULATION TESTBEDS

Gaining access to realistic grid models and data owned by utility companies can be difficult due to privacy and non-disclosure issues. More importantly, in many circumstances even if real data are obtained they may not be sufficient for studying the detailed operation of the entire system because of their limited coverage. To resolve this problem several CPS smart grid simulation testbeds have recently been developed to facilitate hardware-in-loop simulation of different grid applications without the need for gaining access to real data. Selected examples of such testbeds in the United States include CPS testbeds at Washington State University using GridStat [108], cloud-assisted wide-area control testbed at North Carolina State University using ExoGENI [107], cyber-security testbeds at Iowa State [119], a microgrid testbed called DyMonDS (Dynamic Monitoring and Decision Systems) at Carnegie-Mellon [120], TCIPG in University of Illinois [121], DETER-lab testbed at University of Southern California [122], CPS testbeds at Idaho National Lab, Cornell University, and Pacific Northwest National Labs, and a big data hub at Texas A&M [123]. A comprehensive list of many other smart grid testbeds and their CPS capabilities was recently presented in the survey paper [124]. Two key questions that most of these testbeds are trying to answer are - (1) is it possible to design sufficiently general CPS standards and protocols to support a mass plug-and-play deployment of a smart grid without sacrificing reliability, data privacy and cyber-security, and (2) if so, then what standards and protocols are required to transform today’s grid into an end-to-end enabler of electric energy services.
A. Hardware Components

Generally speaking, the physical component of these testbeds are comprised of Real-Time Digital Simulators (RTDS) and Opal-RT. These are power system simulator tools that allow real-time simulation of both transmission and distribution models with a time-step of 50 microseconds. The RTDS comes with its own proprietary software known as RSCAD, which allows the user to develop detailed dynamic models of various components in prototype power systems. The RTDS also comes with digital cards that allow external hardware to interface with the simulation. For example, the Gigabit Transceiver Analog Output (GTAO) card allows the user to view low-level signals proportional to voltages and currents at different buses of the system in real-time. The GTAO card generates voltage and current waveforms, and communicates them to sensors such as relays, circuit breakers, and PMUs. The PMUs measure these signals, and send the resulting digitized phasor data calculations to the PDCs. The PDC time-stamps and collects the data from all the PMUs, and sends them to the server for display and archival, when requested. The hardware and the software layers of these testbeds are integrated with each other to create a substantion-like environment within the confines of research laboratories. The two layers symbiotically capture power system dynamic simulations as if these measurements were made by real sensors installed at the high-voltage buses of a real transmission substation.

B. Cyber and Software Components

The cyber-layer, on the other hand, is generally emulated by either a local-area network or a local cloud service. The ExoGENI-WAMS testbed at NC State [107], for example, is connected to a state-funded, metro-scale, multi-layered advanced dynamic optical network testbed called Breakable Experimental Network (BEN) that connects distributed cloud resources in local universities [125]. It allows one to set up dynamic multi-layer connections of up to 10 Gbps between different sites. One may simulate different types of disturbance events in power system models in RTDS, collect the emulated grid responses via PMUs and other sensors, communicate these data streams via BEN, and run virtual computing nodes at various sites in the ExoGENI cloud overlaid on top of BEN to execute distributed estimation and control algorithms. Some open questions for these types of set-ups in the future are, for example - where to deploy the computing facilities to better facilitate data collection and processing, and how to design better communication topologies.

C. A Network of Remote Testbeds

One pertinent question is whether these different simulation testbeds at different locations should be conjoined with each other to create a much bigger nationwide network of CPS testbeds. And if yes, then what are the most common challenges for such remote testbed federation? Developing protocols for usability by different users, and potential safety hazards are two important challenges, for example. Researchers are also contemplating making their testbeds open to public for accelerating research in the power and CPS community, but a robust economic and ethics model for sharing access to private resources still needs to be developed. Should there be a common centralized simulation testbed for accessing power system model and data, one must also resolve standardization issues, communication issues, maintenance costs, and strategies for sustainability.

D. Interoperability: Databases and User Interfaces

One of the major challenges for the users of the hundreds of existing simulations is that none of them are compatible with each other. Using two different simulations require keeping up two different databases of input data, and being familiar with two different sets of graphical outputs. This is not only true for different types of applications but also of the same application marketed by different vendors. Thus, in the current state of art it is impossible to integrate these different simulation programs. The easiest way to encourage interoperability is to standardize the databases. The data that go into these databases are proprietary to the utilities, and if the utilities can agree on using a standard database the simulation vendors will have to adopt it. In the USA, the National Institute for Standards and Technology (NIST) has been tasked to develop such standards. An earlier standard called the Common Information Model (CIM) is now an IEC standard, and is slowly being adopted at different rates in different countries. A similar effort should be made to standardize user interfaces. If the database and user interface for a simulation is standardized, the ability to integrate different simulators as mentioned above would become much simpler.

X. Conclusions

In this paper, we covered the state of the art of power system simulations, which has evolved since the 1960s by utilizing the rapidly increasing power of digital computation. Increased computational capabilities have resulted in more accurate modeling and more powerful algorithms that allow engineers many more analytical tools at their fingertips to obtain results. The challenge, however, is arising from a different direction. The grid itself is changing because of the proliferation of new technologies. New sources of renewable generation that are intermittent and have no rotating inertia, are being added rapidly. New types of loads such as electric vehicles and smart buildings are also proliferating. Power electronic converters and controllers are being introduced to connect these new generation sources, load and storage devices to the grid. Many of these sources are being added to the distribution system and on the customer side of the meter, thus making the operation of the grid more complicated.

Added to this, the tremendous improvement in computer and communication technologies over the past decade, in addition to improving simulation capabilities, has also improved the operation and control of the power grid. The modern grid is being overlaid with more sensors, communications, computers, information processors, and controllers (ICT) so that it can be better monitored and controlled. The combination of all of these modern technology makes the grid the largest cyber-physical system (CPS) in the world. The challenge is that all these new technologies including the ICT must be modeled...
and simulated together. We highlighted these challenges in modeling, power electronics, co-simulation, cyber-physical systems and simulation technologies. We are optimistic that these challenges will be met by even more judicious use of computational technology. Growth in computing power shows no signs of slowing down, so we do not foresee any limitations on model size or algorithm speed. However, the ability to utilize such powerful simulations depends on how easy their handling can be made to the engineers. Moreover, power systems today are gradually becoming an integral part of other interconnected infrastructures such as gas networks, transportation networks, communication networks, water networks, economics, and food chain networks. Thus, inter-operability of simulation programs will become a key to minimizing the manual effort needed to set up and run co-simulations of these large interacting systems, and interpret the results.

XI. ACKNOWLEDGEMENTS

The first author would like to thank Tomonori Sadamoto (Tokyo Institute of Technology), Ryan Goodfellow (Information Sciences Institute), Yufeng Xin (Renaissance Computing Institute), Pramod Khargonekar (University of California Irvine), and Abhishek Jain (NC State University) for helpful discussions on different parts of this paper.

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Global Network for Synchrophasor Solutions: http://gnssconsortium.org


GENI: www.geni.net

Aruna Chakrabortty received her PhD degree in Electrical Engineering from Rensselaer Polytechnic Institute, Troy, NY in 2008. She is currently an Associate Professor in the Electrical and Computer Engineering department of North Carolina State University, Raleigh, NC. Her research interests are in all branches of control theory with applications to power systems, especially in wide-area monitoring, stability, and control of large power systems using Synchrophasors. He is particularly interested in investigating different cyber-physical modeling and control challenges for the next-generation power grid, at both transmission and distribution levels. He currently serves as an Associate Editor for the IEEE Control Systems Society Conference Editorial Board (2012-present) and also for the IEEE Transactions on Control Systems Technology (2015-present). He received the NSF CAREER award in 2011.

Anjan Bose has over forty years of experience in industry and academia, as an engineer, educator, and administrator. He is well known as a technical leader in the power grid control industry, a researcher in electric power engineering, an educator in engineering, and an administrator in higher education. He is a Regents Professor at Washington State University (WSU), where he also served as the Dean of Engineering and Architecture (1998-2005) and in 2012-13 served as a Senior Advisor to the US Department of Energy (DOE) in the Obama administration. Dr. Bose is a Member of the US National Academy of Engineering (2003) and has served on many National Academy Committees. He is a founding Member of the Washington State Academy of Sciences and has been elected as its President. He is also a Foreign Fellow of the Indian National Academy of Engineering. He is a Fellow of the IEEE and is active in several international professional societies. He was the recipient of the Outstanding Power Engineering Educator Award (1994), the Third Millennium Medal (2000) and the Herman Halperin Electric Transmission & Distribution Award (2006) from the IEEE. He has been recognized as a distinguished alumnus of the Indian Institute of Technology, Kharagpur (2005) and the College of Engineering at Iowa State University (1993).