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GMLC Extreme Event Modeling -- Slow-Dynamics Models for Renewable Energy Resources

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GMLC 1.4.17: Extreme Event Modeling Task 1.3: Slow-Dynamics Models for Renewable Energy Resources

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1 Introduction

The need for slow dynamics models of renewable resources in cascade modeling essentially arises from the challenges associated with the increased use of solar and wind electric power. Indeed, the main challenge is that the power produced by wind and sunlight is not consistent; thus, renewable energy resources tend to have variable output power on many different timescales, including the timescales that a cascade unfolds.

The variable nature of variable energy resources and a wide range of timescales present many difficulties for planning and understanding how to integrate intermittent resources into the existing grid and how these resources impact the reliability and security of the bulk power system. Having accurate models of renewable energy resources is thus critical to assessing their impact on cascade modeling since spatial and temporal variability of wind and solar photovoltaics (PV) resources crosses the domain boundaries of the existing simulators. The failure to include renewable energy variation in cascade simulations can significantly underestimate the extent and impact a cascade might have.

Considering all these facts, power engineers have begun to explore the impacts of large-scale deployment of renewable energy (e.g., wind and solar PV) resources on power system stability. However, there are no universally accepted modeling/simulation platforms that allow the technical community to study issues concerning high renewable penetration scenarios such as ramp events as well as other long-term phenomena (e.g., automatic generation control (AGC)), thus making it difficult to analyze the potential implications of renewable energy resources' dynamics in both the short and long timeframes, ranging from subseconds to several hours. This is mainly attributed to the dual nature of the representation of power system dynamics by differential-algebraic equations in transient stability studies. For this reason, there is a need to address issues arising from the extended-term regime via the use of variable time-step integration methods [1]. To be specific, the numerical integration methods used for performing dynamic power system simulation should have the flexibility to lower the integration time step to capture fast system response and to increase it when the system dynamics evolve slowly [2].

At present, the time-domain stability analysis in power system studies is concerned with phenomena in the tens of milliseconds' to several minutes' timeframe. To illustrate, time-domain simulators, such as GE PSLF™ or Siemens PTI PSS®E, can be executed in multiple domains, but rely on manual control for switching or gloss over potentially important dynamic aspects. Whereas, other simulators, such as DNV KEMA's KERMIT, can run for longer time horizons to capture the slow dynamics, but do not entirely capture the short-term dynamics that can greatly affect system stability. In the academic literature, some efforts have been made by researchers to characterize the effect of slowly varying events, e.g., renewable variability and load variation, on dynamic performance of power grids, highlighting the importance of performing extended-term dynamic simulations [3, 4].

The GMLC 1.4.17 Project is refining the current tools used to simulate longer-term dynamics, which will pave the way for extended-term dynamic simulation for online cascading analysis with multiple time resolutions and horizons. This approach captures power system phenomena ranging from fast dynamics of machines and exciters to cascading events triggered by slow dynamics associated with wind/solar ramping and AGC. Efforts include the study of wind variability events with durations that are longer than normal dynamic simulation timeframes. The goal is to characterize the system's ability to respond to these types of events, incorporate the events in cascading analyses, and use long-term dynamic simulations to assess sustained and sudden renewable variability events. The approach is being developed and validated using Lawrence Livermore National Laboratory (LLNL)'s GridDyn[1] product—an open-source power transmission system simulator—and a variant of Siemens PTI PSS®E model [5, 6]. These current efforts focus on analyzing wind slow dynamics' impacts on cascading events. The model includes the Western Electricity Coordinating Council (WECC) Type-3 and Type-4 generic wind turbine models that are being implemented on GridDyn, including generator/converter, converter control, pitch control, torque control models, etc.

The remainder of this report is organized as follows: in Section 2, the timescales of typical power system events associated with slow-changing dynamics are presented. In Section 3, the generic models of wind and solar PV generation are explained. In Section 4, the survey of events and models attributed to slowly varying dynamics of renewable resources is presented. In Section 5, the efforts being undertaken to address slow-dynamics model testing and validation are discussed. Finally, Section 6 concludes the report by highlighting the benefits of the task efforts as well as the planned outcomes.

2 Temporal Landscape of Slow System Dynamics

The transient behavior of a power system ranges from the dynamics of lightning strikes to those of generation dispatch and load following, covering several decades of the time domain as shown in Figure 1.

Tools and methods to study power system events are presented in Table 1. Fundamentally, the existing framework for power system studies involves modeling and simulation in three distinct timeframes: **(i)** "steady-state" models and studies to investigate system loading

[1] Available online at `https://github.com/LLNL/GridDyn`.

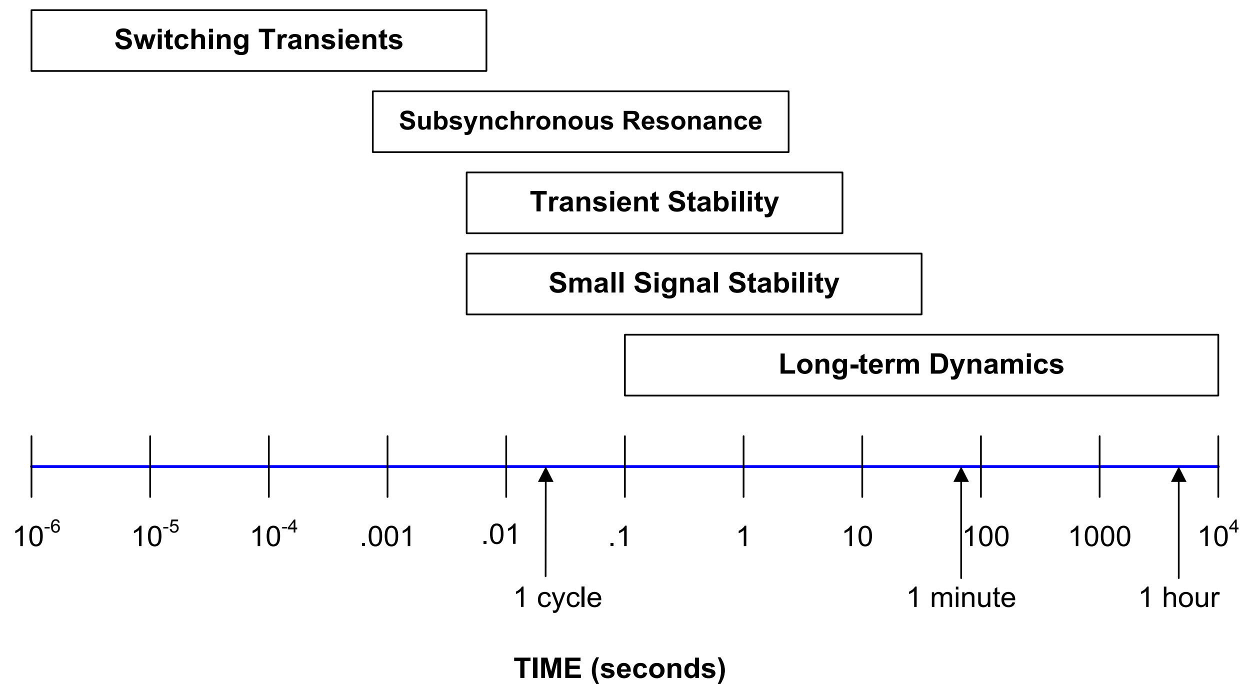

Figure 1. Timescales of different dynamic phenomena.

conditions and voltage profiles; **(ii)** "transient stability" models and simulation tools to investigate the electromechanical interactions of classical rotating generators with one another; and **(iii)** "electromagnetic transient" models and simulation tools to investigate high-speed phenomena such as lightning strikes and faults. For each of these timeframes, power engineers have devised models and mathematical solution methods suitable for each problem. Indeed, for steady-state models, a positive-sequence power flow which involves solving a set of nonlinear algebraic equations is typically employed. Transient stability simulations involve positive-sequence dynamic simulation in which reactive network components are modeled in form of algebraic equations; whereas, controller models can be described by differential equations. On the other hand, electromagnetic transient analysis requires a full three-phase simulation in which components are modeled as differential equations. However, there are no universally accepted toolsets that allow the power engineering community to study issues related to high renewable penetration scenarios such as ramp events as well as other long-term phenomena like fault-induced delayed voltage recovery (FIDVR) and automatic generation control (AGC)[2]. This is mainly because the timeframes associated with wind and solar intermittency is challenging to model with classical transient-stability simulation tools.

[2]AGC is an automatic control system used for continually adjusting the output of generating units, in response to moment-by-moment changes in the load.

Table 1. Power system studies: types, their timescales, tools utilized, and phenomena of interest.

Type of Study	Timescale	Toolset	Examples of Phenomena
Electro-magnetic Transients	10^{-6} to 10^{-2} seconds	Full three-phase simulation where all components are modeled as differential equations	• Faults • Lightning strikes • Harmonics • Switching transients
Transient Stability	10^{-2} to 10 seconds	Typically positive-sequence simulation with reactive network components modeled as algebraic equations	• Generator controls • Motor stalls • Inertia dynamics
(Capability Gap)	10 seconds to hours	No standard toolset exists. Oftentimes these studies are performed by analyzing a set of power-flow cases.	• Automatic Generation Control (AGC) • Ramp events • Frequency response • Fault-induced delayed voltage recovery (FIDVR)
Steady State (Static)	hours to years	Positive-sequence power flow which involves solution of a set of nonlinear algebraic equations (not a time-domain simulation)	• Low-voltage conditions • System losses and economics • Equipment overloading

Therefore, in long-term stability studies, power grid actions and operations that involve slowly changing system dynamics need to be taken into consideration. The events that can have impacts on long-term dynamic behavior include wind/solar variability and ramp events, thermodynamic changes from boiler control action, load following in power plants, hour-to-hour load fluctuations, on-load transformer tap change, economic load dispatch, etc. Again, it should be kept in mind that timeframe of these actions can vary from seconds to hours.

3 Existing Status of Modeling Renewable Generation

This section provides an overview of the models of renewable generation that are presently available.

3.1 Wind Generation

The increased penetration of renewable energy generation poses significant questions concerning the ability of the power system to maintain reliable operation. Indeed, the U.S. Department of Energy (DOE) is targeting 20% wind penetration by 2030, or equivalently, integration of approximately 300 GW of wind energy into the U.S. grid [7]. Large-scale wind resources are being connected to the bulk transmission grid, acting as the primary instrument to transfer the energy generated from the wind resources to the load centers. Most of the existing wind generator technologies generate electricity asynchronously. The variability of wind energy resources introduces complexities and factors that must be carefully analyzed to understand the impact of increased wind penetration on power grid performance [8].

Presently, most wind turbine technologies use power electronics and advanced reactive power compensation as an integral part of wind turbine generator and wind power plant. Under dynamic transients, the behavior of modern wind turbines must be accurately simulated to predict the response of the wind power plant. Inaccurate representation of wind-turbine generators (WTGs) in bulk power system studies may imperil the reliability of power grids by either conducing to excessive overbuild of transmission systems due to pessimistic models, or to inadequate transmission system investment based on optimistic models.

To this end, turbine manufacturers have developed dynamic models for their WTGs. These dynamic models are typically user-written models in commercially available power system simulation software platforms (e.g., Siemens PTI PSS®E, GE PSLF™, DigSILENT PowerFactory, etc.). Detailed three-phase equipment level models of WTGs used for internal design purposes are also often developed by manufacturers in either their own simulation platforms or commercial software tools including PSCAD® or MATLAB® Simulink.

WECC Wind Generator Modeling Group initiated the development of generic models of the four different types of wind turbines. These generic wind turbine models are now available as part of the main model library for the two widely used commercial power system simulation tools. In parallel with the WECC effort, IEEE Power & Energy Society (PES) has also established "The IEEE Working Group on Dynamic Performance of Wind Power Generation" to investigate modeling issues. This Working Group is expanding the efforts of generic dynamic modeling for wind power plants and focusing on model validation [9].

Wind turbines can be classified based on the technology used as either fixed speed or variable speed. A fixed-speed wind turbine is directly connected to the grid system. A variable-speed turbine, however, is interfaced to the grid using power-electronics equipment. Modern large wind turbines are all variable-speed machines. They typically incorporate pitch control and include either a doubly fed induction generator (DFIG) or a permanent-magnet synchronous generator.

Nearly all commercially available wind power plants utilize any of the four WTG technologies listed below:

- Type-1 — Fixed-speed wind generators with squirrel-cage induction generators
- Type-2 — Wind generators with wound-rotor induction generators and limited speed variation through an external resistor
- Type-3 — Variable-speed, doubly fed asynchronous generators with rotor-side converter
- Type-4 — Permanent-magnet synchronous machine or an induction generator with a full converter interface and variable-speed range

Figures 2(a)–(d) show the topologies of the generators for each type of WTG. In what follows, a brief description of these WTG technologies will be provided.

Type-1 WTGs The schematic of the Type-1 WTG model is illustrated in Figure 2(a). In these types of WTGs, the induction generator is directly connected to the bulk power grid.

A Type-1 WTG is an induction generator with simple controls. In common with any induction generator, the Type-1 WTGs absorb reactive power. A majority of commercial Type-1 WTGs utilize multiple stages of switched capacitor banks at the turbine terminals to correct the steady-state power factor at the WTG terminals to unity. With a slow-changing wind speed, the individual capacitors switch in and out. Meanwhile, capacitor banks are used to provide reactive power (var) support.

Type-2 WTGs Type-2 WTGs consist of a wound-rotor induction generator with a variable external resistance connected in series with the rotor winding. Similar to Type-1 WTGs, Type-2 WTGs are directly coupled induction generators and employ capacitors for power-factor correction. The Type-2 WTGs typically use rotor resistance control to realize output power control. The rotor resistance control (fast) and the pitch control (slow) work in unison to adjust speed, lower mechanical stress, and enhance stability during a disturbance event.

A schematic of the Type-2 WTG model is illustrated in Figure 2(b).

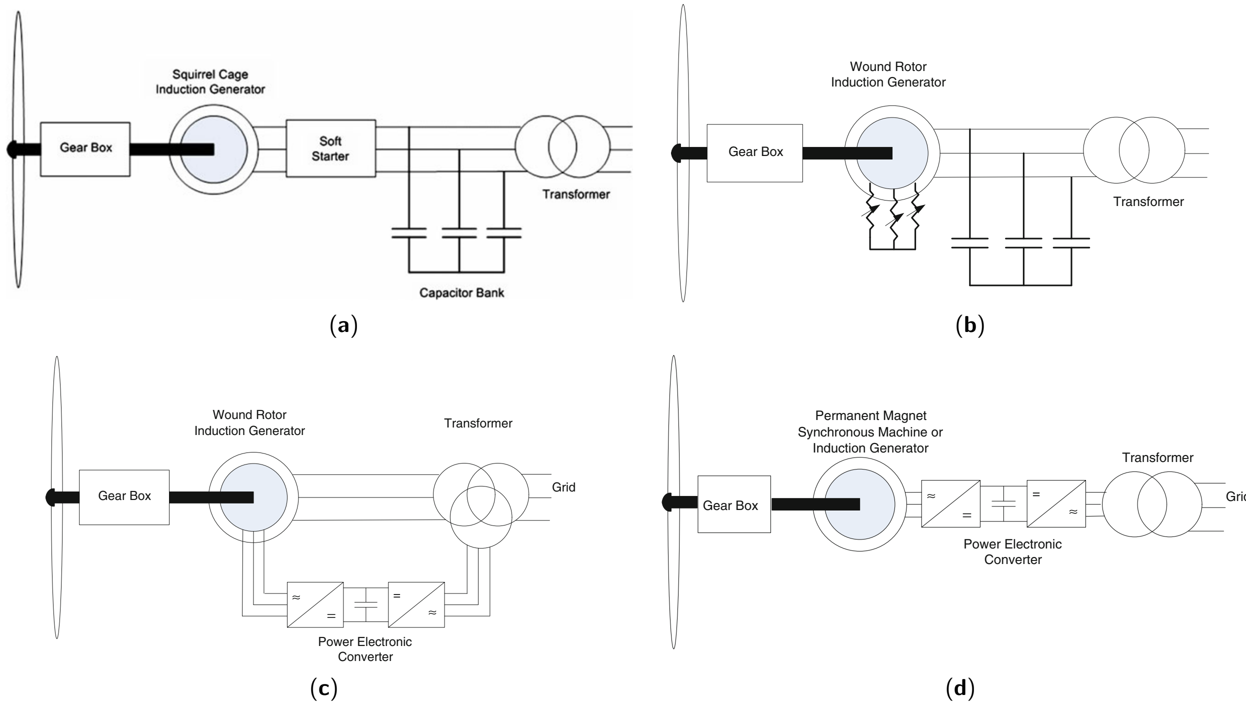

Figure 2. Schematics of generic WTG technologies: **(a)** Type-1, **(b)** Type-2, **(c)** Type-3, and **(d)** Type-4; from [8].

Type-3 WTGs This type of WTG is a variable-speed machine that includes a wind turbine with a DFIG. Thus, Type-3 WTGs are frequently referred to as DFIGs. Presently, they are being utilized predominantly in wind farms all over the world.

The electrical characteristics of Type-3 WTGs are dictated by interactions between a wound-rotor induction generator and a back-to-back inverter. The inverter excites the rotor of the induction generator with a variable ac source. The rotor winding is connected using slip rings to a machine-side converter. The machine-side converter is coupled through a dc-bus capacitor to the grid-side converter which is connected to the grid via a transformer. The mechanical speed of the machine can be adjusted by operating the rotor circuit at a variable frequency. A schematic of the Type-3 WTG model is depicted in Figure 2(c).

The WECC Type-3 model is divided into four modules, as shown in Figure 3. Type-3 WTGs usually offers plant-level reactive power support since the converter control model includes reactive power control options.

As shown in Figure 4(a), the Type-3 generator/converter model provides the interface between the WTG and the grid. In the turbine model, the mechanical state equations are included; however, the flux dynamics are eliminated to reflect the rapid response of the converter. As a result, a controlled-current source calculates the needed injected current

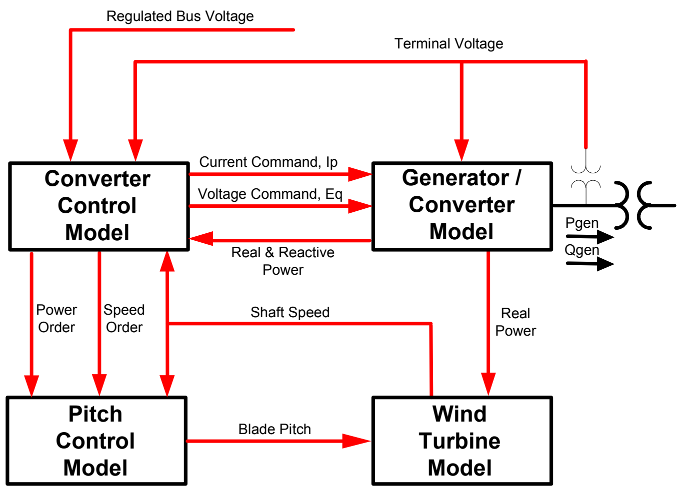

Figure 3. Type-3 WTG dynamic model connectivity, from [10].

into the grid in response to commands from the reactive and active power (torque) control models depicted in Figures 4(b) and 4(c). This model also embodies low-voltage power logic (LVPL) and fast-acting converter controls that have the ability to reduce the reactive current output when the voltage is very high. The LVPL can be used to mitigate system stress during and after sustained faults by constraining the real current command with an upper limit and a ramp rate limit.

The Type-3 WTG converter control model is composed of reactive (Q) and active power (P) control modules, as shown in Figures 4(b) and 4(c), respectively. These modules govern the reactive and active power to be delivered to the bulk grid through the magnetizing voltage and current commands to the generator, $E_{\mathrm{q\ cmd}}$ and $I_{\mathrm{p\ cmd}}$, respectively.

The pitch controller for the generic Type-3 WTG model is illustrated in Figure 4(d). In this model, the pitch control consists of two proportional-integral (PI) controllers that act on the speed and power errors.

Type-4 WTGs This category of WTG is also a variable-speed generator equipped with a fully rated converter that is used to connect the stator of the machine to the grid. The generator could be either a permanent-magnet synchronous machine or a wound-rotor induction generator. In addition to having a wide speed range and being capable of extracting maximum power, these generators have both independent active and reactive power control. A schematic of Type-4 WTG model is displayed in Figure 2(d).

Figure 5 illustrates the modules and connectivity of the generic Type-4 WTG model. Type-4 generic model is structurally similar to the Type-3 model, excluding the pitch con-

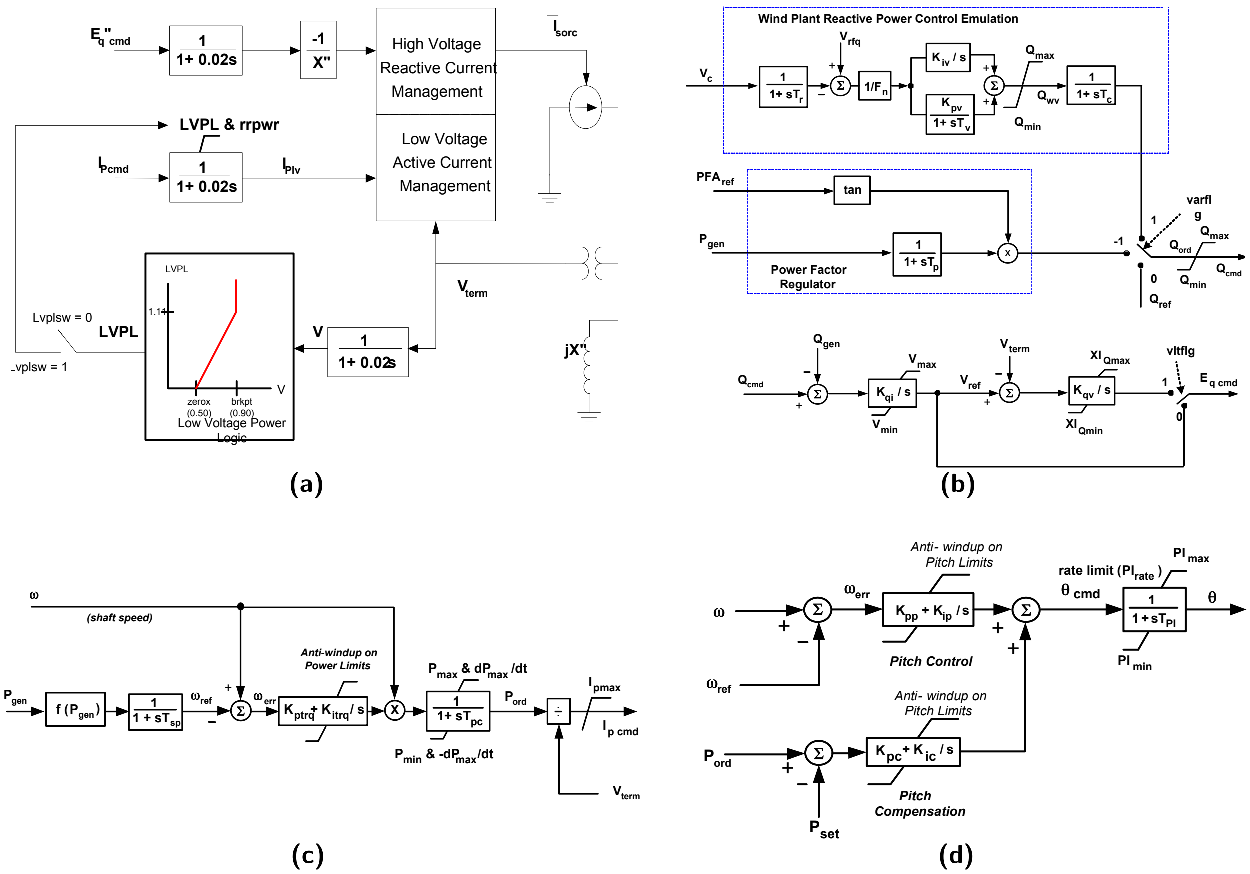

Figure 4. Type-3 WTG models: **(a)** generator/converter, **(b)** reactive power (Q) control, **(c)** active power (torque or P) control, and **(d)** pitch control model; from [10].

trol module. The generator/converter part of the model is similar to the Type-3 WTG generator/converter model, aside from the fact that Type-4 WTG model takes reactive and active current commands as inputs as shown in Figure 6.

The converter control model illustrated in Figure 7(a) calculates the active and reactive power delivered to the network. The structure of the controller model is mostly similar to the reactive power control model of the Type-3 WTG; however, it incorporates logic to specify the current limits.

The converter current limit model is shown in Figure 7(b). This module prevents the real and reactive currents from exceeding converter capacity.

The Type-4 generic WTG model also includes the simplified turbine model shown in Figure 8.

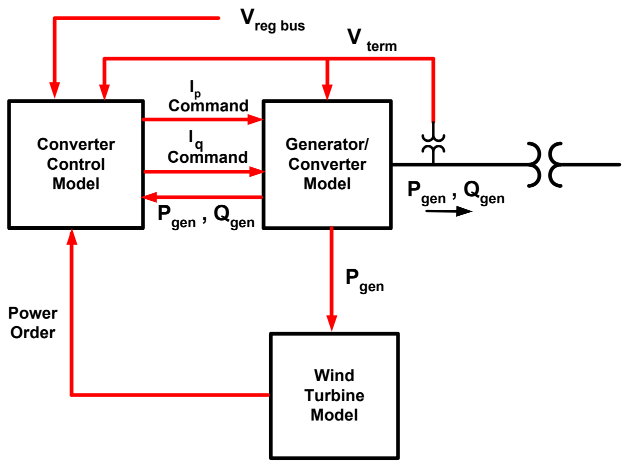

Figure 5. Type-4 WTG dynamic model connectivity, from [10].

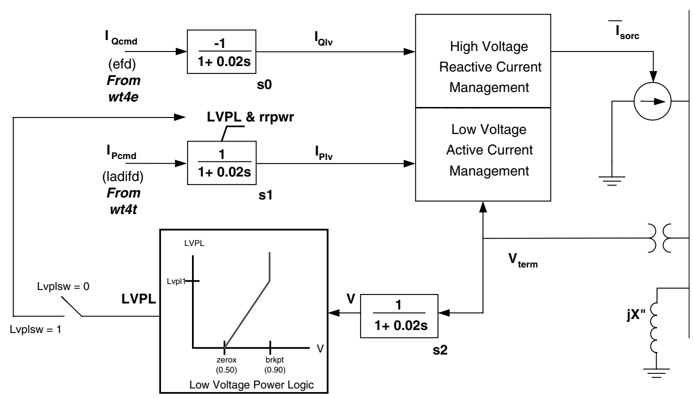

Figure 6. Type-4 WTG generator/converter model, from [10].

3.2 Solar PV Generation

Solar PV systems for power generation are becoming a significant portion of generation in many regions in North America. PV or solar arrays consist of a huge number of solar cells connected in series and parallel. These cells generate a dc voltage when they are exposed to sunlight due to the photovoltaic effect. In order to use the dc power produced by the PV array in an ac power system, the dc power must be converted to 60-Hz ac (in North America). There are several power-electronics-based converter concepts that can realize this, which can be divided into two broad categories: line-commutated converters (LCCs) and self-commutated, or typically referred to as voltage-source converters (VSCs). LCCs use thyristors as their controlled switching device. LCC systems must be operated in a network with an ac source. On the contrary, VSC systems are self-commutating, that is, the power-electronics switching devices (e.g., insulated-gate bipolar transistors, IGBTs) employed can

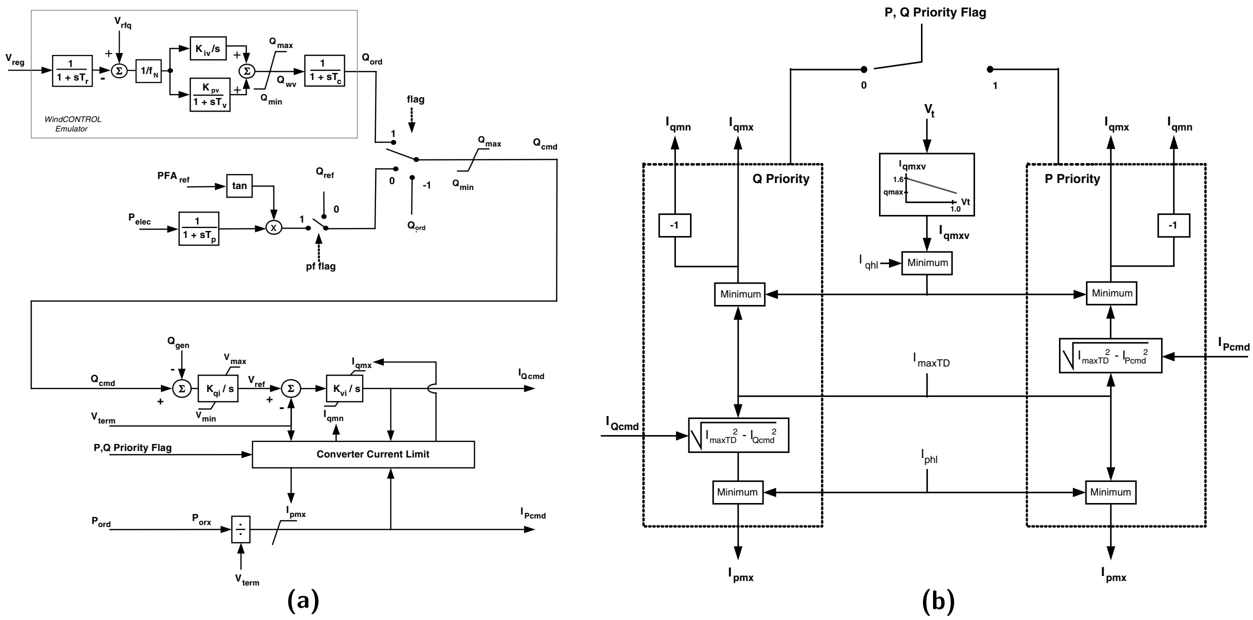

Figure 7. Type-4 WTG converter **(a)** control and **(b)** current limit models, from [10].

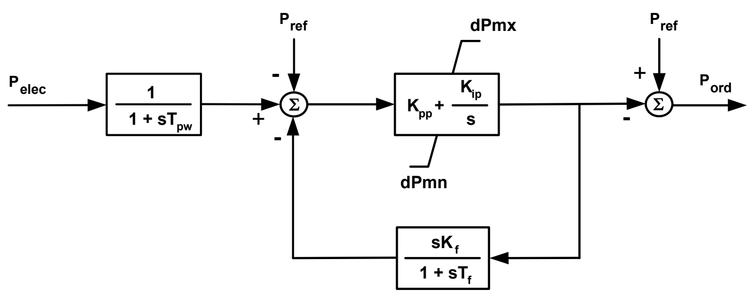

Figure 8. Type-4 WTG wind turbine model, from [10].

be completely controlled and adjust the power factor as seen on the ac side to a range within the current rating of the device. Due to advances in the technology, most power-electronics converters used in PV systems are of the VSC type.

From a power-flow and short-circuit analysis standpoint, the behavior of PV technologies is similar to that of a Type-4 WTG because of the VSC interface, and because its power factor can be controlled based on the control capability of the VSC. Its short-circuit response might be limited to the current limit affected by the VSC when the grid is subject to a fault. From a modeling perspective, there are some user-written manufacturer-specific models developed by various PV manufacturers.

Presently, the the WECC Renewable Energy Modeling Task Force (REMTF) has been addressing the development of generic solar PV models for dynamic simulations in stability studies [11]. The overall model structure of the generic solar PV system dynamic model is depicted in Figure 9. This model consists of three modules: the Renewable Energy Generator/Converter (REGC_A) module that provides current injections into the network solution; the Renewable Energy Electrical Control (REEC_B) module for local active and reactive power control; and the Renewable Energy Plant-Level Control (REPC_A) module that allows for plant-level active and reactive power control.

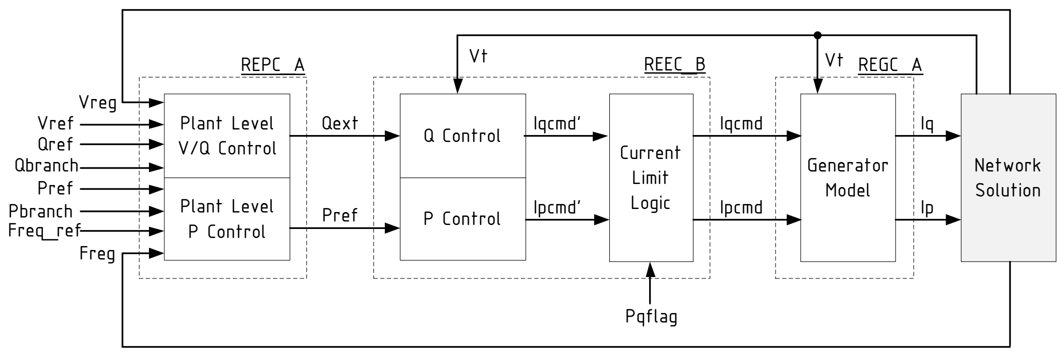

Figure 9. The interconnection diagram for the WECC generic solar PV system model, from [11].

The function of the plant-level controller is to generate reference real and reactive power for the electrical control using values from the network solution. Then, the electrical control transforms reference real and reactive power into current commands for the converter. Lastly, the generator/converter model incorporates the current commands to produce current injections.

Renewable Energy Generator/Converter (REGC_A) Module The REGC_A module is displayed in Figure 10(a). The algorithms used within this module mimic "fast" control actions. This module include the following control capabilities:

- User-selectable reactive current management during high-voltage events at the generator (inverter) terminal bus;
- Active current management during low voltage events to emulate the response of the inverter phase-locked loop (PLL) controls during voltage dips; and
- Power logic during low-voltage events to allow for a controlled response of active current during and immediately after voltage dips.

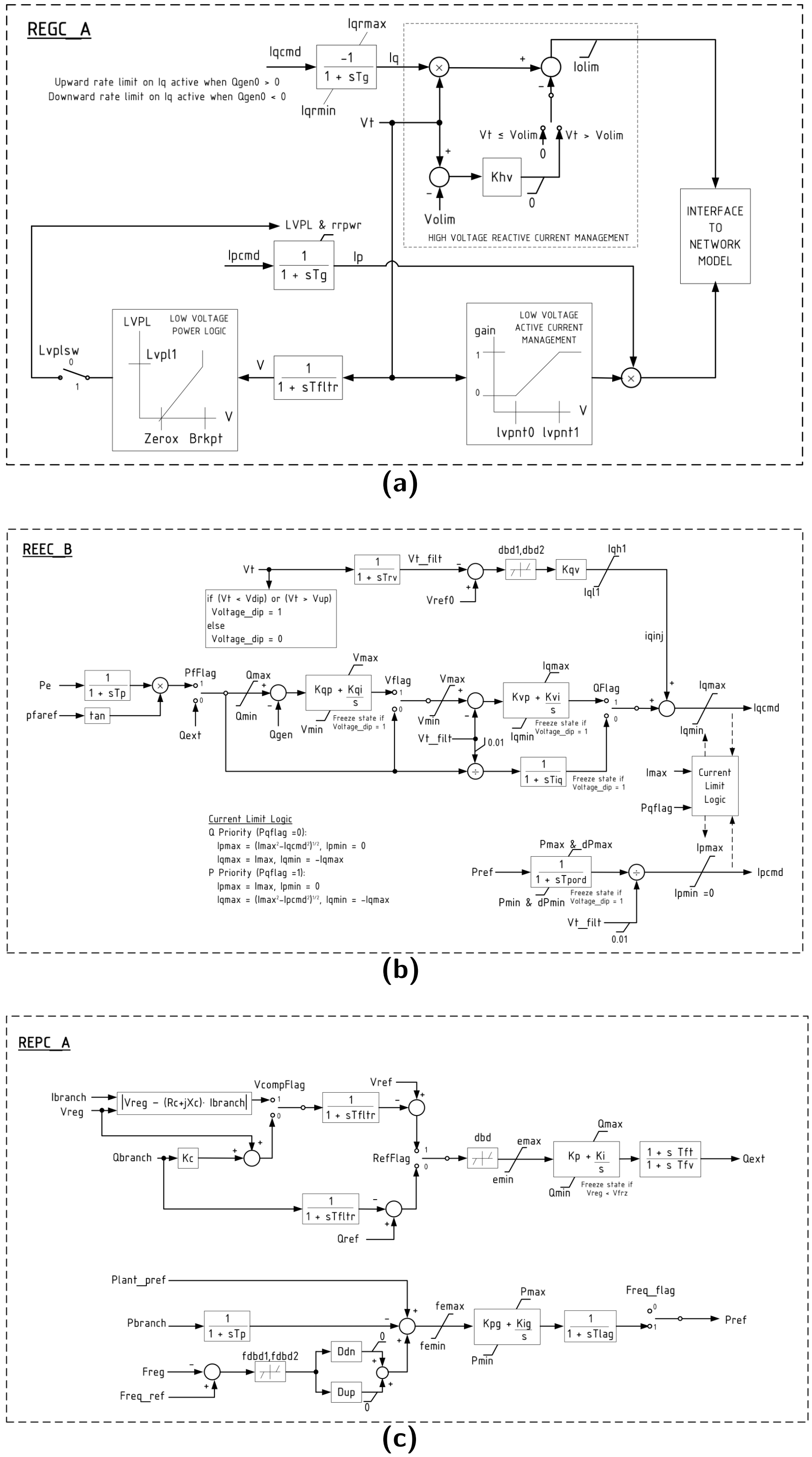

Figure 10. Model block diagrams of **(a)** REGC_A, **(b)** REEC_B, and **(c)** REPC_A modules, from [11].

Renewable Energy Electrical Control (REEC_B) Module The REEC_B module is shown in Figure 10(b). The structure of this module can be divided into two parts: the active and reactive power control subsystems. In the active power control subsystem, the reference real power is passed through a first-order, low-pass filter and divided by the terminal voltage to generate the active current command. On the other hand, the reactive power control scheme allows for proportional control of the terminal voltage. The two PI loops in the center of Figure 10(b) allow for either local voltage control or local coordinated Q/V control.

Renewable Energy Plant-Level Control (REPC_A) Module The REPC_A module is illustrated in Figure 10(c). This module consists of two independent control loops which generate reference real and reactive power. The role of the real power control loop is to modulate the real power output of the PV plant to support system frequency and maintain a constant real power output. In the reactive power control loop, the user selects between plant-level voltage and reactive power control using the "*RefFlag*" parameter.

4 Events and Models Comprising Slow System Dynamics

4.1 Wind/Solar Variability

The power grid is designed to handle significant variability in loads over timescales ranging from seconds to years. Despite the inherent variability in the power grid, the addition of wind and solar power generation to the system introduces increased variability that must be managed by the system operator. At high penetration levels, wind and solar power generation can induce steeper ramp rates, and cause other generators to operate at reduced output. Hence, it can be difficult to manage this variability if existing generators do not have the required ramping capability.

In general, the relative variability of wind decreases with the aggregation of more wind power outputs. Figure 11 illustrates one-second data for nearly nine hours from a wind plant with several interconnection points. The data are normalized to the mean output of each group of wind turbines. The top panel shows the normalized variability of 200 turbines; whereas, the bottom panel shows the output of 15 turbines with considerable variability. From Figure 11, it can be inferred that the normalized wind production variability can be reduced with aggregation.

The variability of wind and solar power has an influence on the power grid operation in different timescales. An abrupt variation in a short period may result in frequency deviation,

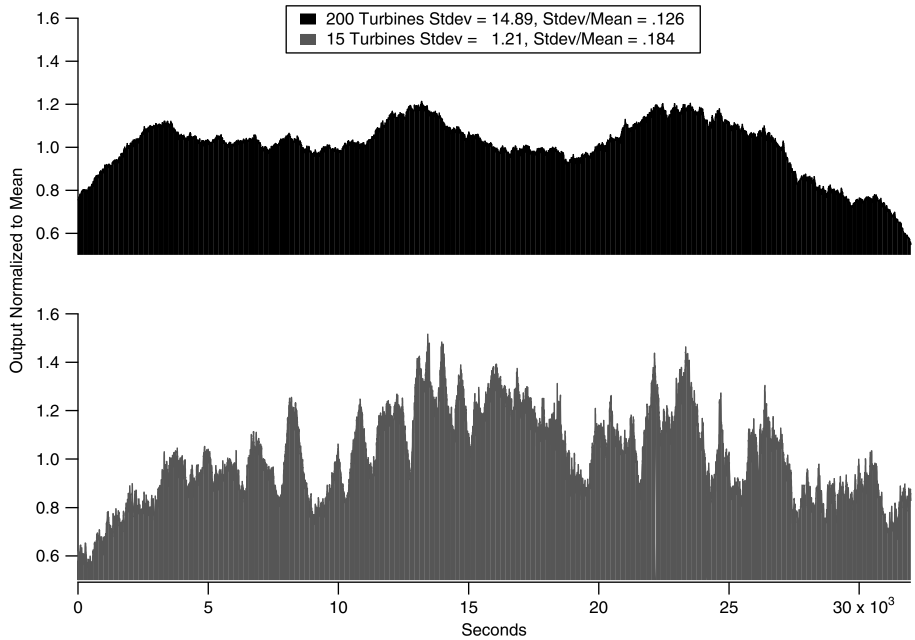

Figure 11. Two cases of second-to-second variability of wind production: a wind plant with 200 wind turbines (the top panel) and a wind plant with 15 wind turbines (the bottom panel) [12].

and thus require a rapid governor response; whereas, a sustained drop over a long period requires an AGC response.

Recently, in a joint effort with Department of Energy (DOE), the Hawaii Natural Energy Institute, the Hawaiian Electric Company, and the General Electric Company (GE) have developed and validated models of the Oahu and Maui electrical grids to study the operational impacts of increasing levels of wind and solar penetration and variability of wind and solar power. Figure 12 depicts the tools used in the Oahu wind and solar integration studies [13, 14]. Of particular interest to slow-dynamics models are transient and long-term stability simulations as well as wind/solar power variability assessments, which are explained below:

GE PSLF^{TM} transient stability model Transient stability simulations can be used to track system behavior (e.g., frequency) during system events. This type of modeling can be used to understand the effect of transient operation of generators on system frequency in a second's timeframe and is used by utilities to guarantee that the system frequency remains stable during critical conditions. In other words, this tool is used to assess short-timescale (subhourly) contingency events associated with high-penetration renewable integration and to characterize the system's ability to respond to these events.

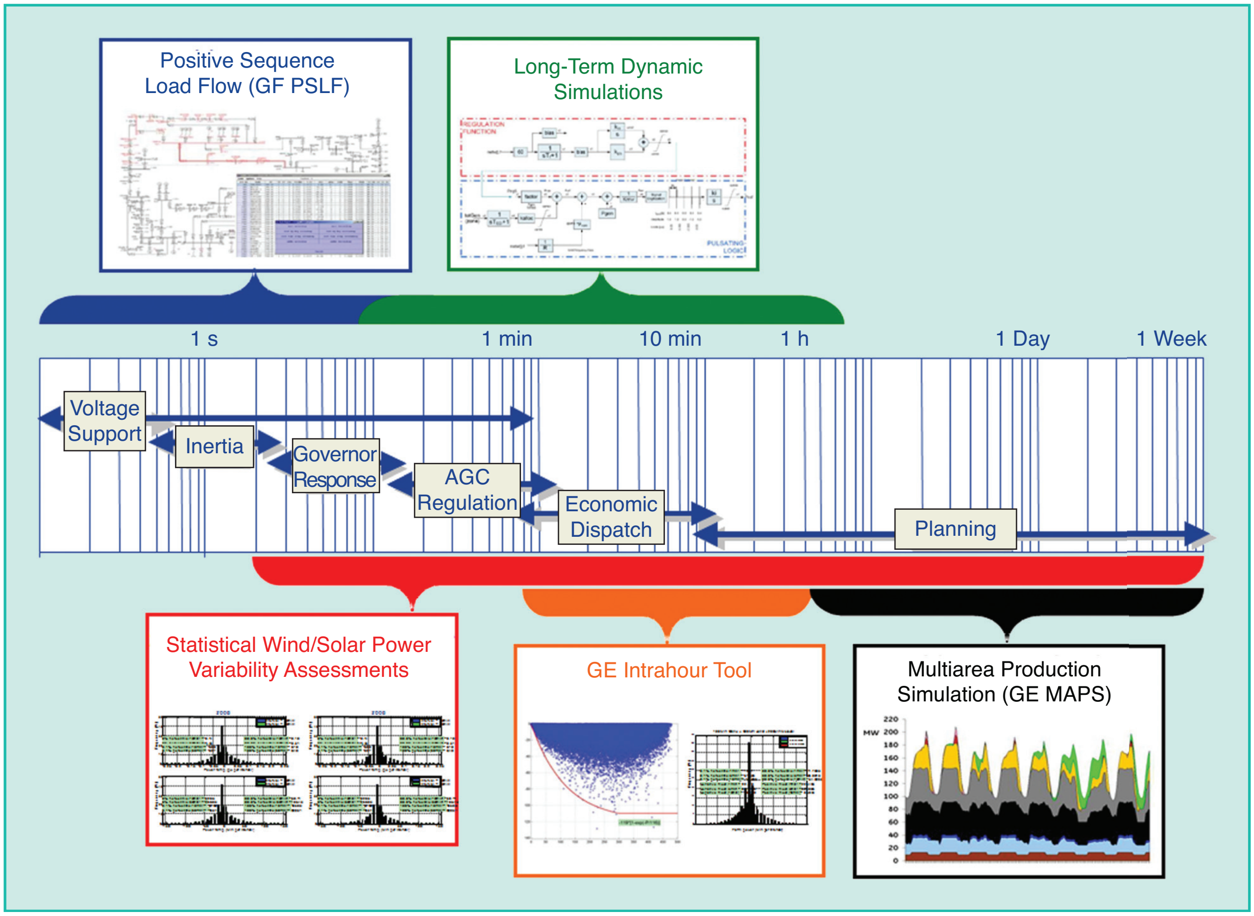

Figure 12. GE power system modeling tools used in Hawaii Solar Integration Study [15].

GE PSLF$^{\text{TM}}$ long-term stability model These simulations assess sustained and sudden renewable resource variability events, capturing governor and AGC response of the system. Second-by-second load and wind variability can be used to drive the full dynamic simulation of the large-scale grid for several thousand seconds. Also, these simulations are used to quantify frequency performance during wind/solar variability events and wind ramp events.

Long-term dynamic models are two to three orders of magnitude longer (in run-time duration) than typical short-term, transient stability simulations. The long-term simulations can be performed with detailed representation of generator rotor flux dynamics and controls, which are representative of short-term dynamics. The models of AGC, load, and available generation variability can be added to capture long-term dynamics. The major role of the AGC is frequency regulation, which involves maintaining the balance between supply and demand.

Assessment of wind, solar and load data Statistical analysis tool assesses the subhourly, hourly, daily, and seasonal variability of wind and solar resources, and quantifies the operating reserve requirement. For instance, wind and solar PV data can be analyzed in different timescales within an hour to understand the net variability imposed on the grid and identify the needed operating reserves to accommodate the subhourly variations in wind and solar power. These reserves can be added on top of the contingency spinning reserve requirement to mitigate wind and solar power variability.

Some other studies investigate the impacts of wind/solar variability on blackout risk. For example, a recent, multi-institutional California Energy Commission study [16] on extreme events reports that increased distributed, renewable generation (e.g., wind and solar PV) with high variability can significantly decrease overall reliability and robustness of the system, leading to increased frequency and size of blackouts. Figure 13(a) shows the blackout frequency as the degree of distribution is increased. It can be clearly seen that with reliable distributed generation (same variability as with centralized generation) the overall blackout frequency decreases, while Figure 13(b) shows a resultant decrease in the sizes of the shed load as the degree of distribution increases. However, Figures 13(a) and 13(b) show a large increase in both the frequency and size of the blackouts when distributed generation has a realistic variability. It is reported in [17] that the distributed generation can, in certain cases, make the system less robust, increasing the risk of occurrence of large blackouts.

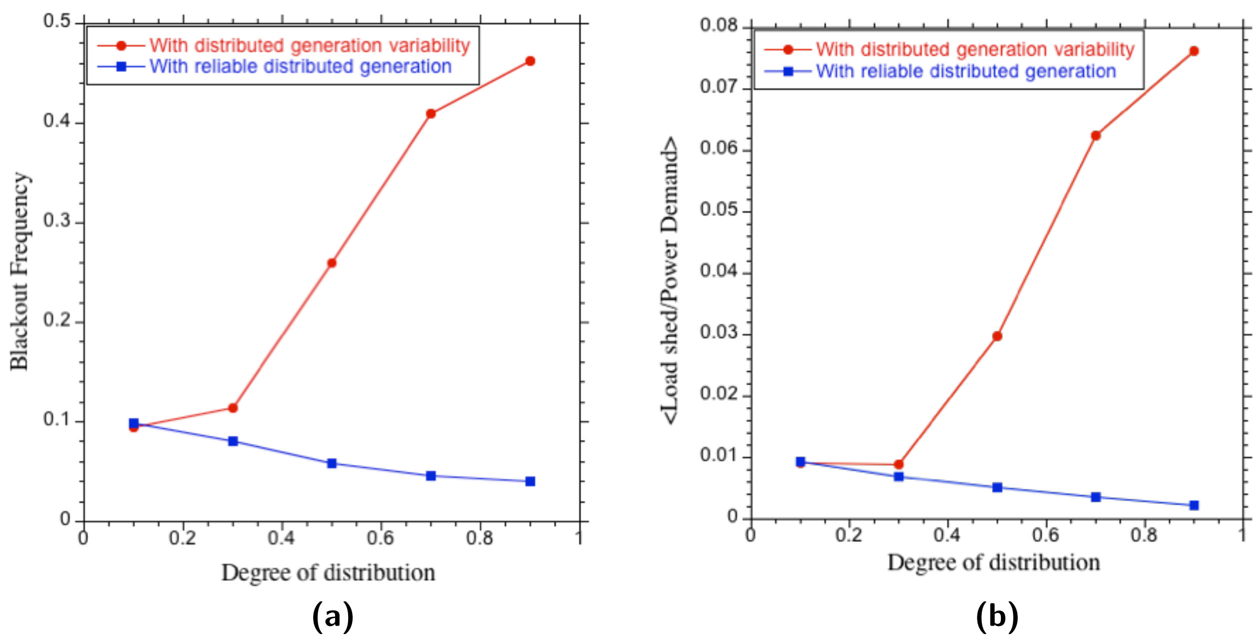

Figure 13. The effect of variability of distributed energy resources on the **(a)** frequency and **(b)** size of blackouts [17].

Ultimately, the abovementioned studies demonstrate that renewable variability should be taken into account when performing long-term cascading analyses, and its potential impacts on the grid stability should be carefully examined.

4.2 Wind/Solar Ramp Events

Given the rapid growth of wind and solar PV penetration, grid operators are required to address integration challenges. A recent case study for Hawaii [18] shows that Oahu and Maui system operations have undergone considerable changes to support renewable energy. The integration challenges for Hawaii are said to be aggravated by the fact that the power grids are isolated islands. It is reported that the islands have experienced significant shifts to the system's net-load curve[3]. This change occurs when the daily load pattern begins to drop during midday hours. These hours of the day, referred to as "onpeak" hours, have been used to be characterized as high-load hours, peaking generators online. With the increase in the renewable penetration, the net-load curve will become even more noticeable.

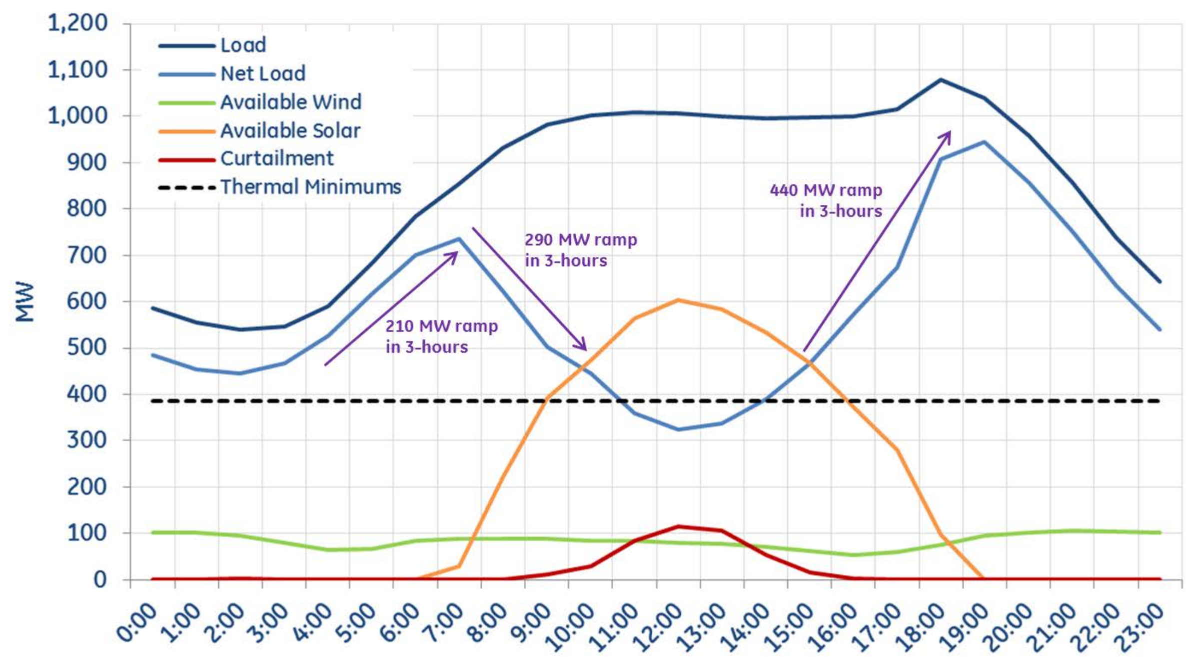

Figure 14. Oahu net-load curve under "high" renewable penetration [18]).

Figure 14 illustrates the net-load curve for Oahu with 300 MW of wind capacity and 860

[3] *Net load* is equal to total load minus wind and solar generation. Net-load curve is oftentimes referred to as the "duck curve".

MW of solar PV capacity for an average day in March 2015. Under these conditions, it can be seen that the early morning ramp-up follows the daily load pattern, which is followed by an even larger ramp as solar generation across the system increases. The solar generation begins to decline throughout the afternoon; therefore, the late afternoon and early evening hours experience a dramatic ramp-up of the net-load energy requirement.

Similarly, Figure 15 illustrates the expected net-load curve for a day in January 2020, under a high-load condition in California [19]. After a sharp upward morning ramp of 8,000 MW in 2 hours, there is sharp downward ramp of nearly 6,500 MW over 2 hours that is followed by a fast evening upward ramp of about 13,500 MW in 2 hours.

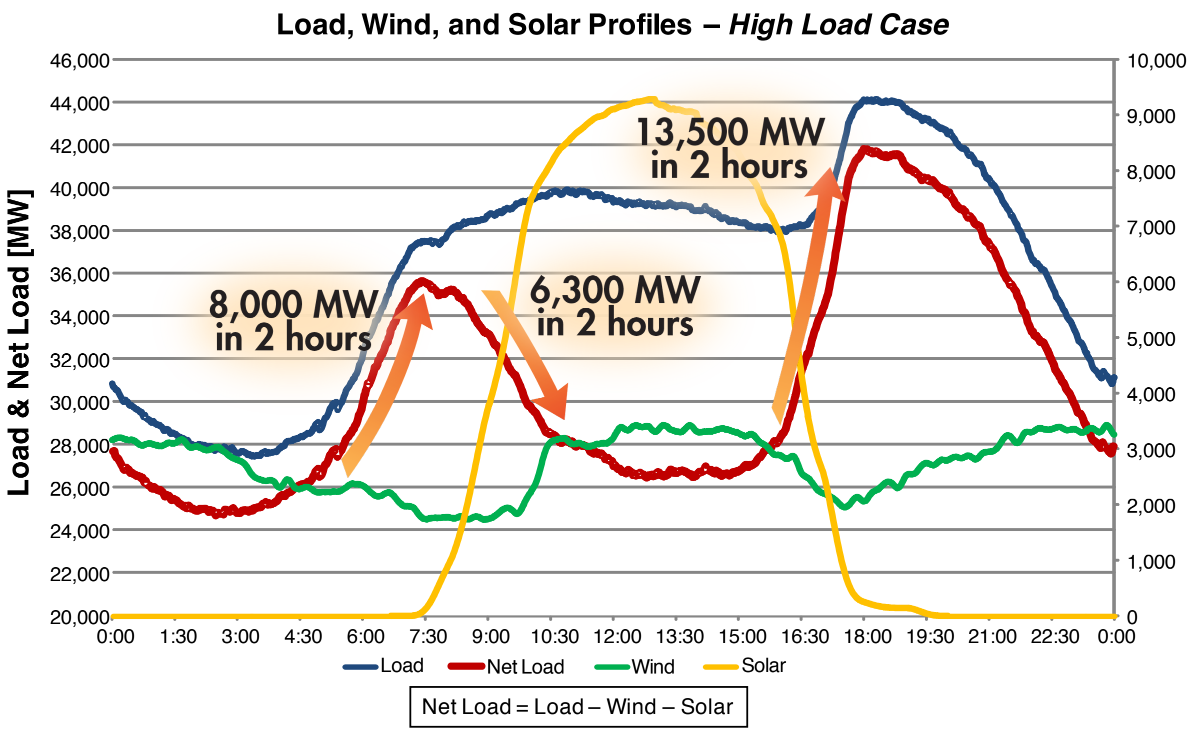

Figure 15. Projected load and renewable generation profiles in January 2020 (©California ISO, 2013; adapted from [19]).

The solar power shown in Figure 15 increases progressively, reaching a peak of 9,000 MW. It should be noted that a partial cloud-cover situation might force solar generation to quickly ramp up and down multiple times as the clouds come and go. Wind generation exhibits similar behavior with rapid drops or increases in output power that would give rise to steep and erratic ramps. To put it another way, Figure 15 shows a forecasted winter day in California, and implies that there may be different ramping requirements during different months.

Some of the key interpretations from Figure 15 are summarized below:

- The stability of the power system is governed mainly by synchronous generators supplied from conventional base load and dispatchable resources. Replacement of conventional generators by wind generators can negatively affect grid stability by reducing the system inertia[4], thereby posing challenges to maintaining grid stability.
- Variations in wind energy and demand within an hour are much more significant for the system. Adequate fast-ramp reserve capacity is required to manage variability of wind generation over this timeframe. Grid operators deploy appropriate backup resources with fast-start capability to follow the variable nature of wind generation.

4.3 Customized (User-written) Wind Generation Models

This section describes the user-written models of Siemens PTI PSS®E developed for extended-term dynamic simulation [6]. These models include an AGC model, a wind generation model, and a load model, which are shown in Figures 16(a)-(c), respectively.

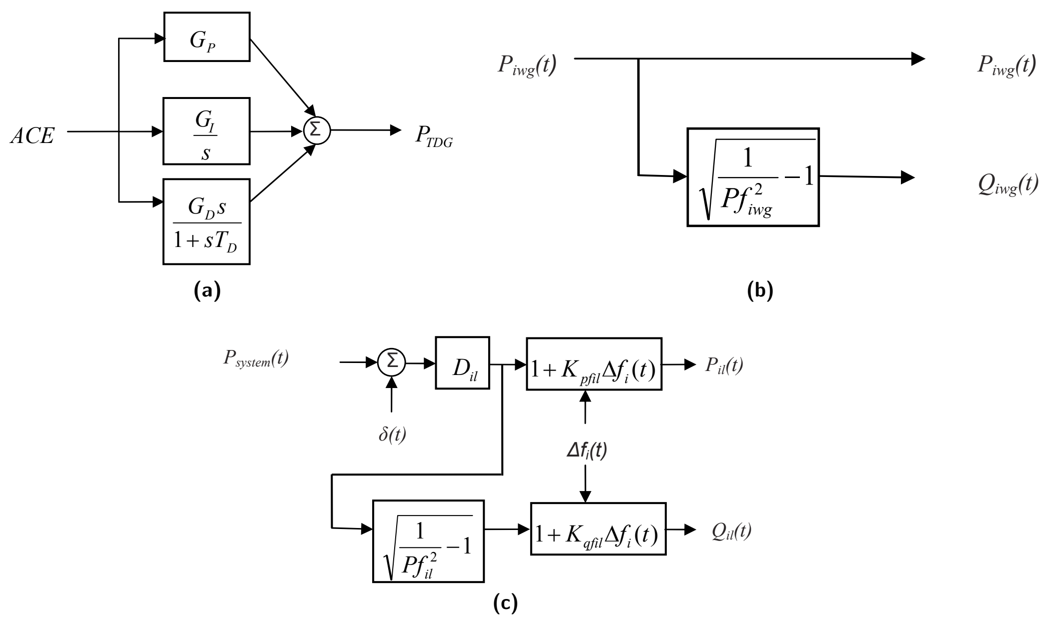

Figure 16. User-written models developed by Siemens PTI PSS®E: **(a)** AGC model, **(b)** wind generation model, and **(c)** load model, from [6].

[4] *Inertia* is a system property whereby the rate of change of frequency during sudden load and generation changes is constrained.

4.3.1 User-written AGC Model

The AGC control logic is composed of two control mechanisms: **(i)** a control-area level and a **(ii)** generating-unit level. At the control-area level, the area control error (ACE) equation is used to compute ACE, which consists of two components: ACE frequency component due to frequency deviation, and ACE interchange component due to actual net interchange deviation. Once ACE is computed, the control area's total desired generation (P_{TDG}) can be determined using a proportional-integral-derivative (PID) control scheme. At the generating-unit level, P_{TDG} is apportioned to each participating unit based on reserve contribution, response speed, unit's operating mode and characteristics, etc.

In this model, ACE is calculated as follows:

$$ACE = -10B\Delta f$$

where B is the frequency bias in MW/0.1 Hz, and Δf is the frequency deviation in Hz.

4.3.2 User-written Wind Generation Model

The wind generation is modeled as a generator with time-varying active power output and constant power factor. The active power output is intermittent. In this model, $P_{iwg}(t)$ is the wind generation active power output, and Pf_{iwg} is the constant wind generation power factor at Bus i. Here, $P_{iwg}(t)$ and $Q_{iwg}(t)$ are the actual active and reactive power of the wind generation at Bus i, respectively.

4.3.3 User-written Load Model

In the load model, it is assumed that each load has constant power factor, and loads vary in time. The system load forecast and distribution factors are utilized to determine loads at buses. In this model, $P_{system}(t)$ is the system load forecast; $\delta(t)$ is the load disturbance; D_{il} is the load distribution factor at Bus i; $\Delta f_i(t)$ is the frequency deviation at Bus i; K_{pfil} and K_{qfil} are the active and reactive load-frequency sensitivities at Bus i, respectively; Pf_{il} is the load power factor at Bus i. $P_{il}(t)$ and $Q_{il}(t)$ are composed of three parts: **(i)** constant-power load, **(ii)** constant-current load, and **(iii)** constant-impedance load, which are then utilized to compute the current injection at Bus i given the voltage at Bus i.

5 Work-in-Progress

Our near-term goal is to validate the Siemens PTI PSS®E model and then successfully demonstrate the use of slow-dynamics models of renewable resources on test-scale systems by coupling GridDyn with Modelica[5]. As part of this effort, we have a library for reading Functional Mock-up Interfaces (FMIs) that are built into GridDyn, whereby model exchange objects are loaded.

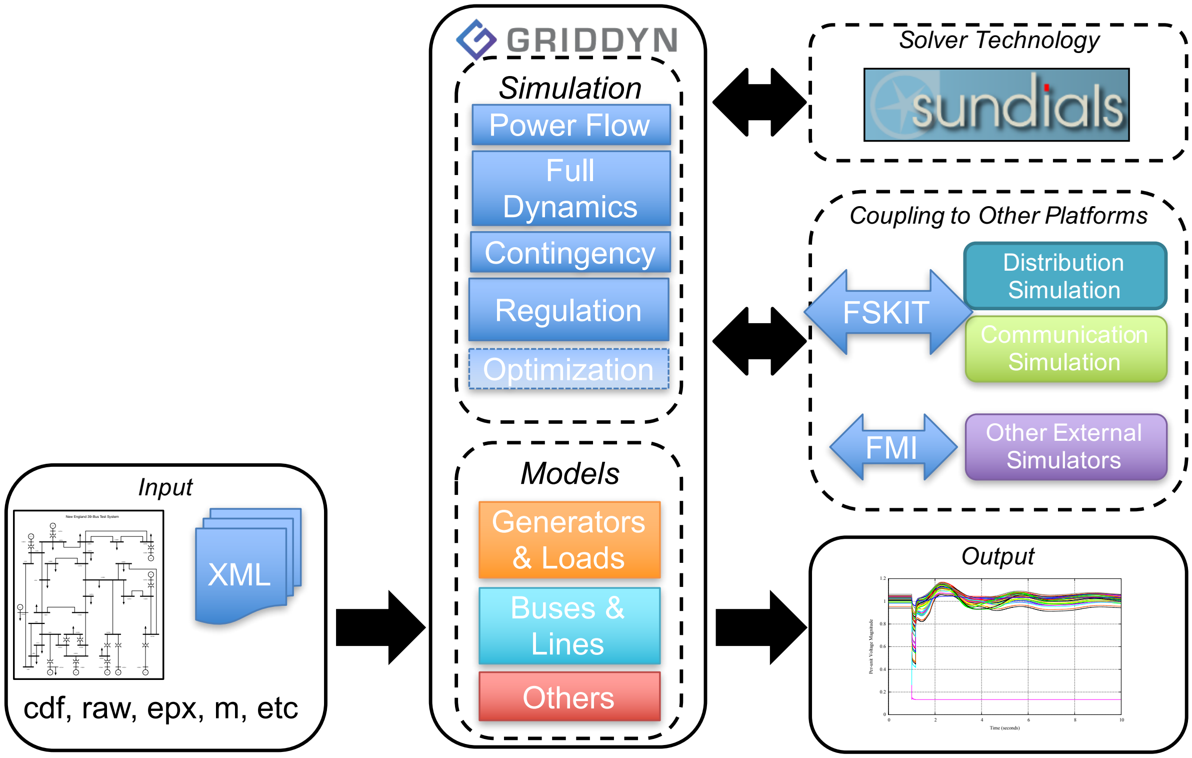

Figure 17. Capabilities of GridDyn and its interaction with different simulation platforms.

As illustrated in Figure 17, GridDyn is an open-source, multi-platform, multi-scale (in time and space), and multi-mode power system simulation platform. It is designed not only for standalone systems but also for high-performance computing environment. GridDyn typically uses `.xml` as input for model definition and supports importing other files through the `.xml`, such as `.cdf`, `.raw`, and `.m`. Being written in C++, the GridDyn code itself has only limited facilities for numeric solutions to the differential-algebraic equations, which define a dynamic power system simulation. Instead, it relies on external libraries, such as SUNDIALS (**SU**ite of **N**onlinear and **DI**fferential-**AL**gebraic Equation **S**olvers), interacting through a solver interface tailored for each individual solver. The models are intended to be very flexible in support for an assortment of numeric approximations and solution models, and define the equations necessary for model evaluation. Dynamic simulation capability

[5] *Modelica* is an object-oriented, declarative, multi-domain modeling language for component-oriented modeling of complex systems.

is achieved through a coupled differential-algebraic solver with variable time stepping; the primary solver used is "IDA" from the SUNDIALS package. It can use the dense solver or the "KLU" sparse solver, which is much faster.

GridDyn can easily be coupled to other platforms. Indeed, it has support capability for integration into "FSKIT" for integrated transmission, distribution, and communication network cosimulation. Thanks to its model and solver flexibility, we will be able to use GridDyn in our test cases that involve extended-term dynamic simulation with slowly changing dynamics of wind generating units.

The test plan to achieve the goals of model validation and demonstration will proceed as follows: First of all, we will generate a set of test cases using the previously described user-written Siemens PTI PSS®E model and its enhanced variant as well as the WECC generic Type-3 and Type-4 WTGs. The next step is to model them in both Modelica and GridDyn. Afterwards, we aim to convert Modelica model to a software library called "Functional Mock-up Unit" (FMU) and run in GridDyn, and finally carry out cross-validation for these test cases to ensure that we obtain the same results. After the validation of these models, we will simulate the scenarios for slow dynamics on the IEEE 39-bus test system.

6 Benefits to the GMLC 1.4.17 and Expected Outcomes

We expect that our efforts will bring several benefits to the Grid Modernization Lab Consortium (GMLC) 1.4.17 *Extreme Event Modeling* Project. First and foremost is the new capability to address model inadequacy of renewables and to incorporate slow system dynamics into the cascade models developed under the umbrella of this project. Basically, this will enable the utilities and system operators/planners to refine current tools used to simulate longer-term dynamics, thereby paving the way for extended-term dynamic simulation for online cascading analyses. Consequently, we will be able to perform detailed cascading analyses with multiple time resolutions and horizons. Our end goal is to disseminate and share our models and results on repositories like SourceForge, BitBucket, and GitHub so that research community can benefit from this work.

At the end of the project, a computational model and software implementation that integrate multiple timescales of cascading events and behavior of renewable energy resources will be delivered. The metric of success for this effort will be to simulate cascading events spanning 1-hour timeframe on a large-scale power grid consisting of more than 10,000 buses in less than a few minutes.

Future work should consider the following efforts:

- Optimal control of distributed generation units for the mitigation of cascading outages can be studied.

- One can determine the optimal value of the percentage of power provided by distributed generation that maximizes the robustness of a system.

- The robustness of power grids to cascading outages aggravated by massive levels of renewable penetration can be quantified using various measures of vulnerability.

- Efficient linear solvers may need to be exploited to accelerate the extended-term simulation of cascading events by efficient utilization of parallel computing.

- In addition to wind generation models, other forms of variable energy resources, such as solar PV and wave energy resources, will need to be considered when analyzing complex unfolding of sequence of cascading events.

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