Extended Grid State Definition Document

V3.4

February 2019

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1.0 Purpose and Basic Definitions

1.1 Purpose

This document provides the definitions of the elements of extended grid state for electric grids. This includes more than just traditional power state; it also includes such elements as asset health and stress accumulation, thermal and other environmental states, and the states of grid connected assets such as third party-owned Distributed Energy Resources (DER), including energy storage.[1]

The purpose of this document is to inform architectural and design aspects of modernized grid sensing and measurement, data architecture, and interoperability standards specification and standards usage. It is intended to be compatible with and possibly to extend existing models such as the IEC[2] Common Information Model. This model is not a list of electricity measurements or data elements (although in some cases a state element maps directly to a measurement). It is an abstract information taxonomy for understanding electric grid operation.

1.2 General Definitions

1.2.1 Electric Grid

The electrical grid is a network that allows for the delivery of electricity from suppliers to consumers. This definition includes electricity transmission and distribution systems, electricity substations, transformers, switchgear, protective devices and systems, power lines, control centers, sensing and measurement, control and communication systems, and associated equipment and assets for electricity delivery (adapted from several sources, including US EIA).

1.2.2 Electric Utility

A corporation, person, agency, authority, or other legal entity or instrumentality aligned with facilities for delivery of electric energy for use primarily by the public. Included are investor-owned electric utilities, municipal and State utilities, Federal electric utilities, and rural electric cooperatives. A few entities that are tariff-based and corporately aligned with companies that own distribution facilities are also included (adapted from the US EIA definition).

1.2.3 State of a Dynamic System

State is the minimum set of values (state variables) that describe the instantaneous condition of a dynamic system. State variables may be continuous (physical systems), discrete (logical systems and processes), or stochastic (such as Markov model states). For many types of systems and for linear systems in particular, the mathematics of state are well defined in the context of differential equation solutions of system dynamics. State has the property that future state of a dynamic system is completely defined by the present state and system inputs only. Knowledge of past state trajectory or past inputs is not necessary. Not all state variables can be measured directly; in some cases they must be computed from

[1] DER is defined to include distributed generation, distributed storage, Demand Response and load control, and energy efficiency. Energy efficiency is somewhat different from the others since it is not invokable in an operational sense, but does figure into system planning.
[2] International Electrotechnical Commission

measurements, possibly combined with models of the physical systems under consideration. By defining state elements, we simultaneously indicate what information is necessary to operate a modernized grid without constraining system designers as to how such information is obtained.

1.2.4 Observability

One view of observability is that it is temporal, geospatial, and topological awareness of all grid variables and assets. Such a definition is intuitive, but does not provide much in the way of analytical tools to work with for developing a grid measurement system. A more formal definition of observability is the ability for any combination of system state and inputs to determine the system state in a finite time using only measurement of system outputs. Observability is the technical basis for "visibility."

1.2.5 Estimation and Forecasting

For electric transmission systems with known or assumed models, a snapshot-based process using a set of sparse state variable measurements, a system model, and a mathematically intense solution method (weighted least squares, linear programming, Newton-Raphson iteration, etc.) performs what is widely known as transmission *state estimation* to complete the set of state values. State estimation for distribution grids is a more complex problem than for transmission, due to topological complexities and the fact that distribution is unbalanced; both factors change on short and long time scales.

A forecast is not a grid state variable, since it does not represent instantaneous condition of the grid but is rather a prediction of future inputs. The forecasts of interest here are for exogenous factors, namely solar flux and wind. In the case of buildings, forecasts of DER availability are related to building state, but also depend on exogenous factors.

2.0 Grid State and Extended Grid State

Grid state has traditionally been confined to power state, meaning the collection of voltages, currents, phase angles, and power flows defining the instantaneous condition of the transmission system. Due to its relationship with grid/generator/load dynamics, system frequency is used as a proxy global state variable for grid balance and stability. The taxonomy chart of Figure 1 below extends the traditional power state definition. Note that it is the concept of *state* for electric grids that is extended, not the concept of *grid*.

The taxonomy does include specific aspects of generation and consumption (load). This is because of the implications these have for understanding grid operation. The taxonomy also includes a number of exogenous factors which act as sources of perturbation for grid operations. These include weather, solar insolation, and water flow. They also include aspects of generation, power and capacity markets, and DER for the reasons that they can either be used for control (to modify grid state) or may act as perturbing factors under the control of actors external to the grid, such as system operators, DER operators, and even hackers.

The taxonomy diagram has been structured into a set of layers, proceeding from the top to what have been arbitrarily labeled Categories (blue), Groups (green), Kinds (orange), Sets (white), and Types (aqua), just to distinguish the layers. At any layer, specific examples (purple) can be attached for clarification purposes. The boxes in the layers are defined and discussed below. Following that, special topics are discussed, namely Estimators, Modelers, Analytics, and Forecasters; and Outage Definition in the Presence of DER and Microgrids.

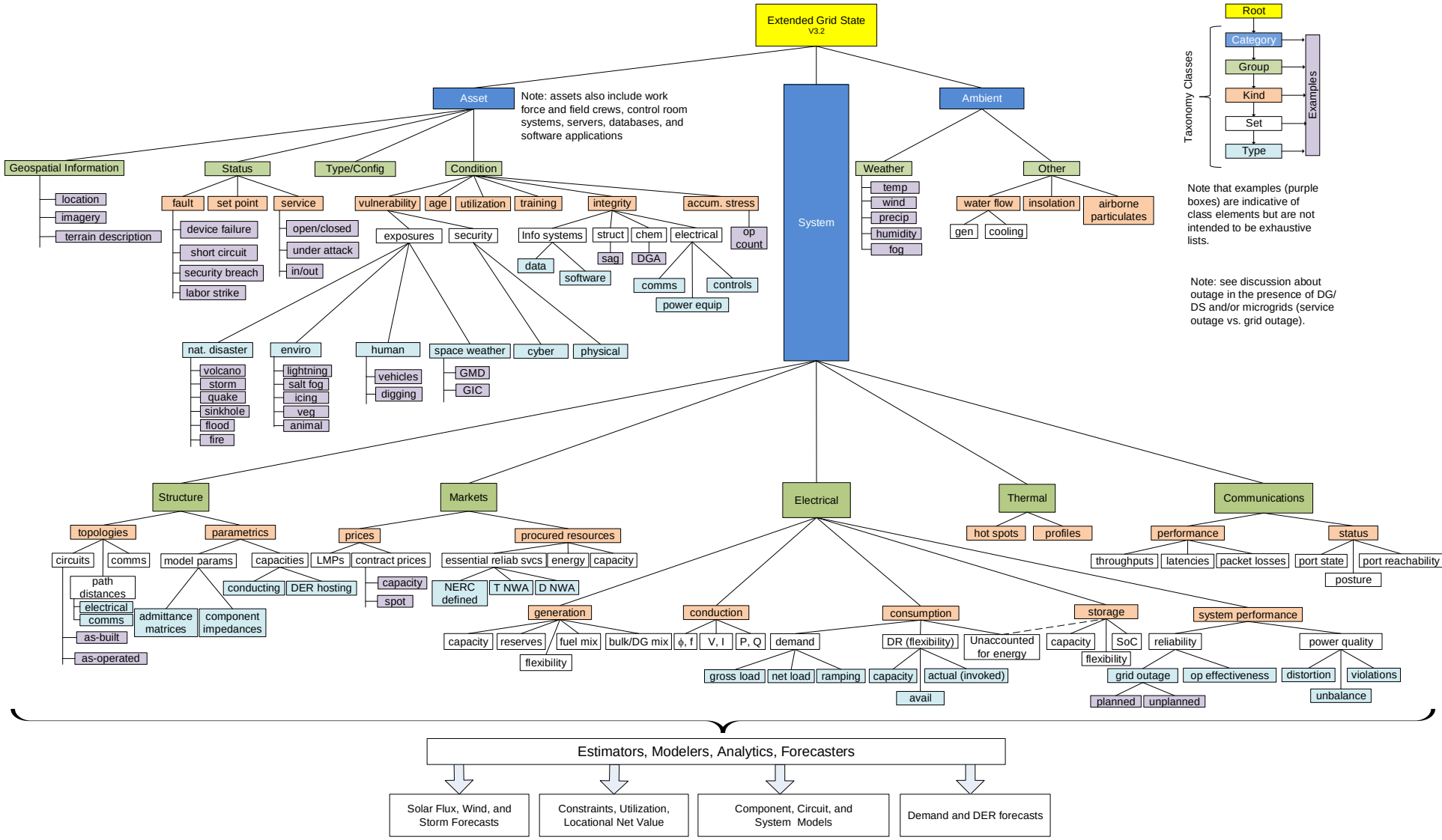

Figure 1. Extended Grid State Taxonomy

2.1 Asset State

2.1.1 Status

A numerical quantity used to indicate the operating mode or status of a power grid component. This state can take discrete values such as for the open/close status of a switch or a circuit breaker, or the position of a tap changer of a tap-changing transformer. It can also take analog values such as settings of protection relay devices. Operating state further breaks down into:

- Set point: The preset value(s) that define the planned operation mode or status of a power grid component which has multiple operation modes or a range for continuous variation of operation status. For example, the setting values of various protection relays.
- Service: The quantity that indicates the real mode or status, including the in- or out-of-service status, under which a power grid component is operating. The tap position of a tap-changing transformer and the open/closed status of a circuit breaker make two examples of service state. Physical and cyber-attack are also included as Service states.
- Fault: An indicator showing that the component is in fault condition. A fault may be a device failure, a short circuit, a physical or cyber security breach, or even a labor strike (given that the work force is a human asset).

2.1.2 Type/Configuration

The information that is common to a number of grid assets and able to distinguish them from others as an identifiable category. The type/configuration state can be defined corresponding to various categories of characteristics such as class, structure (e.g., dry/oil type transformers), geometry arrangement (e.g., horizontal/delta-configured transmission line), connectivity (e.g., "Y"/delta connection for 3-phase device/system), or operating mechanism (e.g., air-break/vacuum circuit break).

2.1.3 Condition

2.1.3.1 Vulnerability

The state to describe or model the inability of grid assets to withstand the disadvantageous effects caused by natural and/or social forces. Its intension consists of two aspects, being exposed to a hostile environment and the failure of protective measures.

Exposures

The state of the grid assets' being exposed to a hostile environment that possibly leads to system failure and other disastrous results. The types of exposures power grid assets and system may experience include:

- Natural disasters such as volcano, storm, quake, sinkhole, flood, and fire, may occur at very low frequency but if happened, would cover a large geographic extent and cause severe damage to grid assets and operation.

- Environmental exposures may include lightning (causing electromagnetic transients in power systems and results in electrical, thermal, or mechanical damages to assets), salt fog (causing flashover of insulators and corrosion of equipment), icing (causing irreversible line conductor sag, flashover of insulators, grounding faults), vegetation (causing vegetation encroachment resulting in grounding faults), and animal (causing grounding faults).
- Human exposures may include the encroachment by human, vehicle, or human activities (ex, digging to break underground cables). Human exposures are usually dangerous for both the personnel and the grid assets that are involved.
- Space weather exposure is often referred to the geomagnetic disturbance that results in harmful effects such as the Geomagnetically Induced Current (GIC).

Security

The state of being vulnerable to attack (either physical or cyber)

- Cyber: Relating to computer/information systems and communication networks
- Physical: Relating grid physical assets, including electrical equipment, personnel, computing hardware and displays

2.1.3.2 Age

The equivalent advanced time period of a grid asset into its lifetime estimated based on the normal operation and maintenance assumption. The effective age of a grid asset is not simply the time since it has been put into service. The age can be affected by many factors such as the stress level and duration under which the asset has been operated, or the quality and frequency of maintenance that has been conducted to the asset. Age also includes aging of the workforces (human assets).

2.1.3.3 Utilization

To what extent a grid asset (or a set of assets) is put to use during a specified time period for the purpose it is designed for. The extent can be referred to full capacity of an asset or the total number of a set of assets. Utilization can also be temporary, or permanent. In practice, “Utilization Rate” is often used to quantify the utilization state of the assets.

2.1.3.4 Integrity

The state of a grid asset being whole with sufficient capacity and health to ensure the normal functionality and operation.

Information Systems

- Data: the completeness, accessibility, and accuracy of data sets needed to operate, characterize, record operating history or otherwise support grid operations and planning. This may include connectivity databases, time series data stores, or other operational or non-operational data stores.
- Software: completeness, accessibility, and Quality Assurance (testing and validation) status of programs and software packages.

Structural

The state of grid assets to hold the physical structure together under a load or force (mechanical, electrical, etc.).

Sag

The difference in elevation between points of supports and the lowest point on a line conductor. Sag can be calculated based on the physics model of catenary since overhead line conductors take the form of a catenary between points. Sag is affected by conductor temperature, weather (ice and wind) loadings, and time. Conductor sag is strongly coupled with tension. The sag-tension characteristics of a line have to be carefully designed to ensure adequate clearance and strength margin of the conductor under all weather and electrical loading conditions.

Chemical

The state of grid assets to maintain a balanced and stable chemical environment to ensure the normal operation of the assets.

- DGA – Dissolved Gas Analysis – used to analyze the health of power transformers by performing chemical analysis on transformer oil.

Electrical

The operational condition of electrical devices and circuits, including power equipment, control devices, and communications devices.

2.1.3.5 Accumulated Stress

A parameter or characteristic to describe the accumulated effects of factors and stresses that can cause the reduction of life/integrity of a power grid component. It is measured and/or monitored for assessing the health condition, forecasting potential failure, and predicting the life of the component. This type of state is usually under periodic measurement or continuous monitoring. Typical grid components that are subject to monitoring of the accumulated stress include, but are not limited to, generators, excitation systems, turbines, governors, transformers, circuit breakers, surge arresters, and batteries. An example of accumulated stress can be the operation counts of the grid components that operate in the step-wise or switching on/off manner.

2.1.4 Geospatial Information

The data to describe the geographic location and characteristics of natural/man-made features of grid assets/components. The geospatial information is geographic and spatial in nature, and takes the forms of coordinates, street address, Global Positioning System (GPS) data, satellite imagery, terrain descriptions, and geotagging.

2.2 System State

System state is the subset of extended grid state that deals with the physical grid and related structures. This includes the traditional power state elements (voltages, currents, power flows, phase angles), but also includes communications, markets, thermal states, and a set of elements characterizing structure for electric circuits and communication networks.

2.2.1 Structure

Structure is defined in the Grid Architecture discipline as an arrangement or pattern of interlinkage of components; organization of a system; the form; the "shape" of a system.

Structure is a fundamental, tangible or intangible notion referring to the recognition, observation, nature, and permanence of patterns and linkages of components. This notion may be tangible, such as a built structure, or an attribute, such as the structure of society. Structure sets the essential bound on a system's possible behavior and the grid is comprised of a number of related structures.[1] The Extended Grid State includes elements for electrical structure (circuits) and communication networks. Other structures exist within and around the grid, including control structure, coordination framework structure, industry structure, market structure, and regulatory structure. These are not included in the definition of extended grid state even though they are used and useful in work on Grid Architecture because they do not relate directly to grid level sensing and measurement.

2.2.1.1 Topologies

Topological state is *the connectivity of grid networks* (electrical, communications, control and coordination, financial/market); it also includes topological location of connected grid and prosumer components which are crucial for planning and control. It can be shown using a graphical diagram or its equivalent matrix description.

Circuits

Electrical topology state is time varying on both fast and slow time scales. Fast changes occur when circuits are reconfigured through switching, and in the case of microgrids, islanding. Slow changes occur due to construction and maintenance, and the phenomenon of "drifting" of service transformer connections from one circuit phase to another during maintenance and repair operations over time. Electric topology state is essentially the structural part of the system model, but not including parametric elements such as admittance. For electric power circuits, topology may be represented in either node-breaker (physical model –IEC Common Information Model) form or bus-branch (logical model –IEEE Common Data Format) form. Circuits are commonly represented in the form of bus-branch models depicted as single line diagrams (see Figure 2 below). For distribution, phase connection of loads and edge devices is important since many are connected to a single phase or to two phases only. Consequently for distribution circuits, the line diagram or other representation must be augmented with phase connection information.

[1] See Grid Architecture Basic Definitions: http://gridarchitecture.pnnl.gov/basic-terms-and-principles.aspx

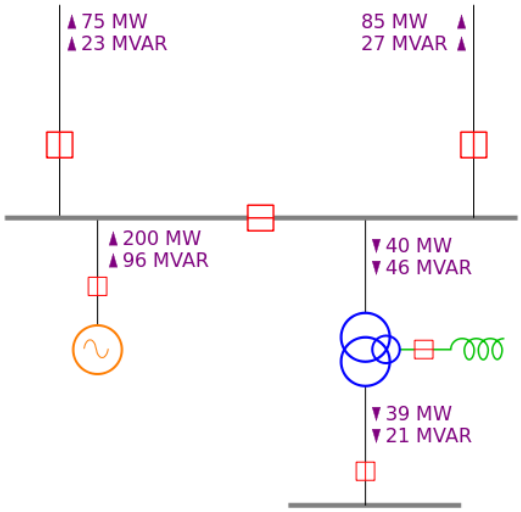

Figure 2. Example Transmission Bus-Branch Single Line Diagram

Communications

Communication network topology, commonly called network connectivity or network topology, has two views. One is a physical view, wherein the topology of the network is represented by network diagram of the type shown in Figure 3. Such a representation shows routers, switches, etc., as nodes (usually rendered as icons) and physical layer links are shown as interconnecting lines.

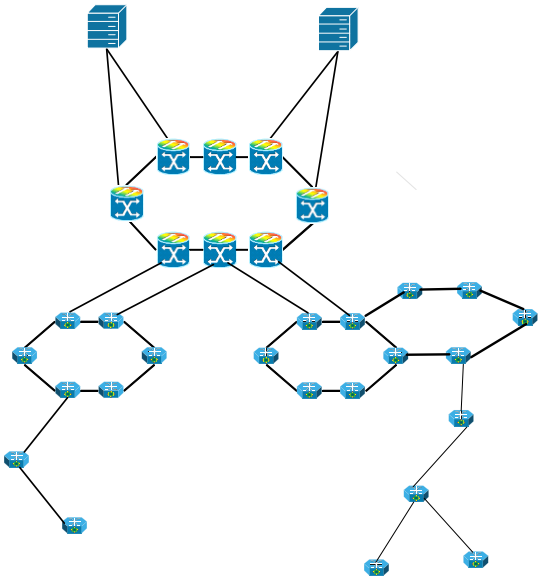

Figure 3. Communication Network Connectivity Diagram

The second view is logical, and shows data flows in a manner that is related to data usage and may impose a logical topology onto the physical network. For example, the underlying physical network may be a mesh, but the logical data flows may be effectively hub-and-spoke. The logical data flow model is constrained by the physical model and is determined both by network protocols and applications. Physical network topology can be time-varying due to link or node failures, device maintenance, etc. Logical

connectivity can vary due to network congestion or other underlying factors and for latency-sensitive applications can become significant. Connectivity may be represented in the form of a graph or equivalent matrix.

The time-varying nature of connectivity in electric grids leads to the need to consider two connectivity models: one for the "as-built" network and one for the 'as-operated' network. The as-built network is the verified form of the network as designed and originally built out; the as-operated mode represents the network in terms of real time operation (controlled switching or routing, link and node failure, etc.). Real time, or as-operated topology is important for automated grid operations *because topology is the structural context within which grid data and control must be interpreted and in which grid data must flow.* For communications networks, as-operated topology depends on physical as-operated topology, network protocols and management, and application factors such as subscription to PIM/SSM[1] data flows.

Path Distances

In addition to topology, structural state includes geospatial elements that depend on component location and link physical routing. Component location has several aspects:

- physical location of components (such as GPS coordinates) or street address (see Asset Geospatial Location)
- topological location (such as the substation, connected bus, feeder and phase)
- path or route distance from a base location, such as a substation

Here we are only concerned with the last - path distance. For electric power circuits, the concept of electrical distance is well-defined and well-known: essentially, electrical distance is path length along conductors for electric power flow. Typical uses would be to specify the location of a fault as being some distance in feet from a substation (along a transmission line or distribution feeder), or to locate a piece of equipment such as s service transformer or a capacitor bank in the same manner. Electrical distance is used to locate both components and circuit faults.

The same concept applies for communication links, especially for long optical fiber runs in wide area communications, where latency can be a concern. For communication networks, it is the distance along the physical medium over which the communication signal must travel. For communication networks, two types of path length are needed: one is the actual route path; the other is the shortest path through the network (assuming a mesh network). These may or may not be the same; actual route path would typically be more dynamic than shortest path.

2.2.1.2 Parametrics

These are dynamic values of key characteristics of grid components, especially impedance (or admittance). Impedances are used in dynamic de-rating and fault location for example and can change with loading, external temperature, cloud cover, etc.

Model Parameters

System models are comprised of a structural part (see Topologies above) and parameter values. In some representations, both are present.

[1] Protocol Independent Multicast/Source Specific Multicast

- Admittance matrices – grid system models are often cast in the form of admittance matrices. Such matrices provide parameter values (the admittances) but the matrix inherently also encodes structure. Consequently, the admittance matrix can be both parametric and topological and some methods have emerged to discover grid connectivity from other grid state-related measurements aimed at estimating the admittance matrix.[1,2]
- Component impedances – impedances are used for voltage drop/rise calculations and in some methods for determining fault locations.

Capacities

Capacity is a typical parameter of concern both bulk system and distribution planning and operation. Capacity generally relates to ability to handle power flow or load or to provide energy or power and in combination with power state elements directly relates to constraints. For example, distribution circuit capacity impacts thermal, voltage, and protection constraints. Transmission line capacity relates in a dynamic manner to congestion and is connected to bulk system organized markets (where they exist) via Locational Marginal Prices (see Markets Prices LMPs).

DER integration has resulted in a newer element of capacity: DER hosting capacity. Distribution feeder circuit DER hosting capacity reflects operating criteria limits in relation to power state and exogenous factors such as existing connected DER. In places where DER integration is increasing this is therefore a dynamic set of state variables related to grid structure and grid parametrics but also varying with DER penetration.

2.2.2 Markets

A market is a physical or virtual place where buyers and sellers choose to interact to trade goods, services, contracts, or financial instruments for money or barter. A market typically involves means for communicating the attributes of the item between buyers and sellers, agreeing on exchange prices and quantities, and effecting physical delivery. Electricity markets are of two main types: spot markets and bilateral markets. Spot markets involve multiple buyers and sellers submitting bids and offers, and the process of market clearing results in market signals, i.e., cleared quantities and prices, that indicate to the participants how to proceed, but do not involve direct relationships between individual buyers and sellers. In contrast, bilateral markets result in contracts between individual buyers and sellers that typically specify a quantity, price, time and location of delivery. Organized central markets do not exist for all parts of the US power grids, but where they do their relationships to grid operation and control make them essential elements of grid operations and therefore require representation in extended grid state. Organized wholesale electricity markets involve a number of market types and market "products" operating on a range of time scales. For grid state purposes, the state of each market is described by clearing prices and quantities of the procured resources. See Appendix B for structure and component models for US electricity markets.

2.2.2.1 Prices

Two kinds of prices are included in the extended grid state definition: one refers directly to market transactions, and the other is a construct that connects physical grids with market operations.

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[1] Yuan, et. al., CalTech, On the Inverse power Flow Problem, Oct. 2016, https://arxiv.org/pdf/1610.06631.pdf

[2] Y Liao, et. al., Stanford University, Urban Distribution Grid Topology Reconstruction, available online: https://pdfs.semanticscholar.org/744e/b4cbd3f4cd26030fa2a1dda467e23157dd4c.pdf

- Contract prices – contract prices are the market clearing prices for the various market products, whether they are capacity, energy, or power (ancillary services).
- LMPs – Locational Marginal Prices are used to connect the physical transmission system operations with markets so as to resolve potential physical congestion issues.

2.2.2.2 Procured Resources

The items traded via the organized wholesale electricity markets are various capacities (such as generation capacity), actual commodity electricity (energy), and various services, generally known as ancillary or more recently essential reliability services. These are bulk energy system views, but for DER, there are potentially additional values and therefore market products presently contemplated but not yet implemented.

- Capacity – for grid state, this is the magnitude of procured capacity, whether it is generation, regulation reserves, or other as needed and specified by the markets
- Energy – commodity electric energy, typically MWh.[1]

Essential Reliability Services

- NERC-defined essential reliability services are inertial support, primary, secondary, and tertiary frequency support, voltage support, and ramping. Not all are unbundled for markets. Typically MW.[2]
- Transmission Non-Wires Alternatives – Use of DER (including load control to avoid new infrastructure investment at the transmission level; this can take various forms mostly impacting apparent load. Typically MW.
- Distribution Non-Wires Alternatives – Use of DER (including load control) to avoid new infrastructure at the distribution level. Typically MW.

2.2.3 Electrical

2.2.3.1 Generation

Generation is the conversion of other primary energy sources into electricity.

Capacity

Generation capacity is the sum of the total nameplate rated capacities of available generation sources. For operational (and where they exist, market reasons) generation capacity may be subdivided into various categories for classes of reserves as well as bulk energy sources.

Reserves

Reserves are amounts of generating capacity held back or available for use in adjusting to real time variable operating conditions. A wide variety of reserve types is recognized in bulk system operations – typically measures in terms of power (i.e. MW).

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[1] MegaWatt-hours
[2] MegaWatts

Flexibility

Flexibility is the amount of reserve generation capacity available to the system operator or balancing authority at any particular time.

Fuel Mix

For a bulk energy system, a variety or primary energy sources may be used. The proportions of these sources (formerly fuels like coal and natural gas, but now including renewable resources as well) is the fuel mix (may also be known as generation mix). Fuel mix can vary dynamically on both short (due to certain renewables) and long (due to conventional fuel economics) time scales. Fuel mix may be expressed in generation capacities or in percentages of total capacity per source type.

Bulk Generation/Distributed Generation Mix

Given the emerging bifurcation of generation (split into bulk system centralized generation plants and edge-connected distributed generation), the mix of these sources is interest. As with the fuel mix, the bulk/distributed generation mix is time-varying on short and long time scales. It is expressible in terms of percentages of total generation capacity.

2.2.3.2 Conduction

Frequency and Phase

In Alternating Current (AC) power systems, the voltage waveform is nominally a sinusoid with a specified frequency (number of cycles per second in the voltage sine wave). Actual frequency can vary and is an indicator of generation/load imbalance in power systems with multiple rotating machine generators and consequently can be treated as a global (electric interconnection system-wide) state variable.

Due to various factors, voltage waveforms in an AC power system exhibit time shifts with respect to a reference waveform. Such shifts can be expressed as angles for a given fixed sinusoid frequency, hence the use of phase angles to describe such shifts. Voltage phase angles are important indicators of power flow direction and magnitude as well as system stability and are measured using synchronized timing across wide areas of a power grid.

Voltage and Current

Voltage is the measure of potential difference between two points in an electric circuit. In AC power systems with multiple generators and loads, voltage is regulated in various ways at various levels. It is thus important to know voltage magnitude at many places in electric power systems.

Current is the movement of electrons or flow of charge between two points driven by a difference in potential. Current is often used as an indicator of the load and loading of conductors and other electrical components. Current can also be utilized in definition of undesirable grid states, such as fault currents.

Real and Reactive Power

Due to the phase relationships between voltage and current in the same circuit, AC power can be considered to split into two parts: real power flow which is consumed by the end user, and reactive power flow, which oscillates between phase-lagging and phase-leading elements in a circuit. Knowledge of all real and reactive power flows in an electric power system is considered basic power state information.

2.2.3.3 Consumption

Demand

Demand is the "load" on the electric system; the total real power required by all of the devise and systems using electricity from the utility at any given time

- Gross load – total amount of demand at any given time, regardless of any behind the meter generation or storage
- Net load – amount of demand seen by the utility, taking into account behind them meter generation and storage; in other words, gross load minus load reduction measures
- Ramping – time rate of increase or decrease of demand

Unaccounted-for Energy

Some electric energy is lost by conversion to heat in conductors and equipment (technical losses) and by diversion (theft of service) and therefore does not contribute to revenue for the utility. Other energy may be used for station service (energy consumed by a generating station for power plant operations) and for spot unmetered loads ("hot pots"). It may also refer to some kinds of energy flows for bulk storage, when used as grid components.

Flexibility (Demand Response)

Flexibility of demand is based on the ability of some loads to respond to external (utility-generated) signals to adjust usage (usually referred to and Demand Response but more generally Flexible Load)

- Capacity – amount of demand that is capable of responding to load adjustment signals from the utility
- Availability – amount of demand capacity that is online and consuming power and therefore could actually be reduced in response to a load adjustment signal (loads that are offline cannot be reduced)
- Actual (invoked) – amount of adjustable demand that is actually reduced by a load adjustment signal at any given time. In other words, the amount of adjustable load that is "activated" by the load adjustment signal – the amount of actual load reduction seen by the utility

2.2.3.4 Storage

Electric energy storage covers a class of components that may be attached to the electric grid at any of various levels and may provide a number of services to the grid. Grid storage falls into two major categories that distinguish their primary externally visible properties and therefore how they are applied. One category can absorb energy from the electric grid and return it directly in the same form; the other category can absorb energy from the electric grid and convert it to another use (heating, transportation) or return it to the grid indirectly. Storage may be reflexive or transitive, as shown in Figure 4 below.

Reflexive storage absorbs energy form the grid and returns it to the grid. Transitive storage absorbs energy from the grid and outputs it to some other system or process, such as thermal storage used for building heat or battery storage used to run a motor to create kinetic energy in the form of transportation). Reflexive storage is further subdivided into direct reflexive (such as a chemical battery with bidirectional power electronics interface) and indirect reflexive (such as use of electricity to pump water into an elevated reservoir, thus converting to potential energy, followed by later using the water to turn a turbine and generator that puts energy back onto the grid). Storage may provide grid services on fast (milliseconds) or slow (hours) response and duration time scales.

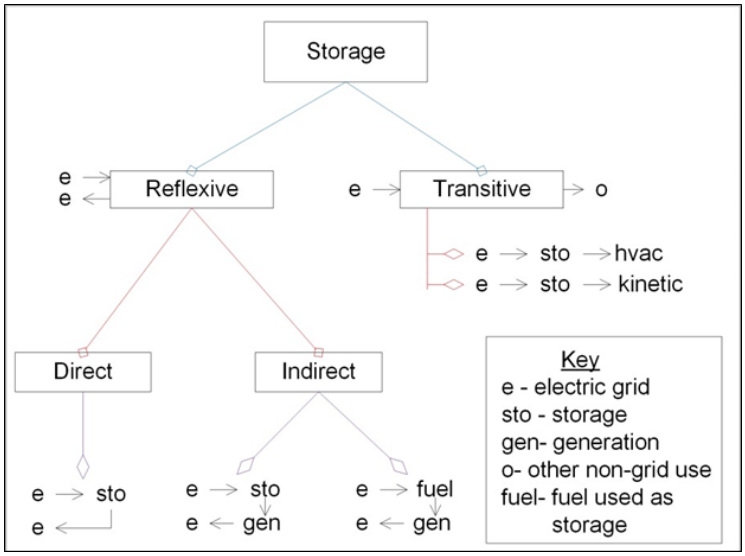

Figure 4. Storage Component Taxonomy Diagram

Energy state (usually referred to as State of Charge for batteries) is the amount of energy stored in a grid storage mechanism, expressed as absolute energy (in MWh, for example) or as a percent of the maximum capacity of the storage unit. Some examples include:

- Potential energy state – for devices that store energy as potential energy (springs, compressed air, flywheels, pumped hydro, etc.), the amount of energy stored at any particular time, but which may not be expressed in electric energy terms; for systems that convert electricity into fuel for later use in electric generation, may be expressed in terms of fuel volume or mass.
- Thermal storage state – energy stored in thermal mass; may be described in terms of heat units like BTUs instead of electric energy units, or may be characterized by average temperature or temperature distribution of the thermal mass.

Capacity

Capacity is the maximum amount of energy that a storage device may hold. It may be expressed in energy units, or as a sustainable transfer rate (e.g. MW) for a period of time (e.g. 4 hours, this form is due to the way certain market procurement mechanisms and grid operation requirements are defined). The maximum transfer rate is a device characteristic, not a grid state variable.

State of Charge

State of Charge refers to the amount of energy actually stored in the storage device at any particular time. May be expressed as a percentage of maximum capacity or as energy or as a sustainable transfer rate for a specified time.

Flexibility

As with grid flexibility in general, this is defined as the storage reserve margin, expressed in the same form as capacity or state of charge, but represents reserve storage capacity. Due to the nature of storage, any given unit may have differing up and down reserve capacities at any particular time.

2.2.3.5 System Performance

Reliability

Grid Outage

Outage state is not a matter of the traditional reliability metrics; it is the set of outage conditions that exist at any particular time on the electric system. This include loss of service (loss of voltage) at the delivery point level, loss of voltage at the circuit or substation level, or loss of voltage at the bulk system (transmission level). Given the existence and growth of distributed generation, distributed storage, and microgrids, the definition of "outage" has become somewhat more nuanced than in the past (see Appendix A below). Fundamentally, loss of ability to supply electric service at any level is an outage, and the state variable is the extent of the outage (endpoints, circuits, systems).

Operational Effectiveness

Operational effectiveness for organizations is a process and practices concept, but here it means correct functional operation of devices, communications, and systems. Measures such as uptime, readiness, and availability do not get directly at the issue either. At a device level, operational effectiveness is defined as the ability to correctly carry out a command or function and is an issue due to device and communication failures. It is measured in a moving window sense as the number of correct operations completed divided by the total number of operations commanded, usually expressed as a percent. Operational effectiveness for a subsystem or a whole system maybe calculated from device values using statistical reliability theory.

Power Quality

Power quality is a measure of the steady state, short and long term deviations in voltage, magnitude waveform and phase angle, which lead to a variation in the service received by consumers. Power quality can be both defined as a steady state condition, time series, or dynamic. Power Quality can be defined as a distortion, violation or unbalance.

Distortions

A distortion is generally a variation in the waveform shape of a voltage signal. Impact of a distorted voltage state is a decrease in operational effectiveness and possible damage to equipment and component health.

Violations

A power quality violation is when the distortion of a waveform, harmonic content or overall voltage level has reached above or below limits defined by standards for safe and healthy grid operation. This could be in the form of harmonic content, steady state voltage, or time series variation up and down in voltage resulting in a degradation in performance of a load (for example lights flickering).

Unbalance

Unbalance in a three phase system occurs when the symmetrical components negative sequence is non zero. Unbalance is common in distribution systems due to unbalanced loads.

2.2.4 Thermal

Electrical equipment can generate and dissipate heat and may also gain heat from insolation. Thermal state refers to key temperatures of grid components. Two forms are included in the definition of extended grid state:

- Hot spot - maximum temperature and its location in a grid component; examples are the winding hot spot in a distribution transformer, or top oil temperature in a power transformer. Hot spot temperature is a single point temperature, which may or may not be directly measureable.
- Profile - temperature distribution on a grid asset. Temperature profile is a collection of temperatures, sampled spatially, such as at regular distances along a transmission line cable.

2.2.5 Communications

Communications networks are integral to utility operations at all levels. Structural state variable issues are covered in the Structure section above. This section describes operational state variables for communication networks.

2.2.5.1 Performance

Network performance is monitored and managed on a real time basis. Key state variables for network performance on a link by link or path by path basis are:

- Throughputs - net rates for data transport; these are actual rates accounting for payloads vs overhead, retries, etc., not raw bandwidth.
- Latency and jitter – time required for packet transport; may consist of several elements such as propagation delay, switching delay, serialization delay, queuing delay, and encryption/decryption delay if link-level encryption is being used. Variation in latency (jitter) may be used in addition to latency.
- Packet losses - percentage of packets dropped (did not make it from end to end) on any particular link or route

2.2.5.2 Status

Status elements reflect functional condition state for communication networks.

- Port state – any of blocking, listening, learning, forwarding, or disabled

- Port reachability – the condition of being able to send to and receive from any particular network port at a particular address, or not, from any other particular port or host
- Posture – configuration and security status (software/firmware versions, protocols, parameter settings, access control, etc.)

2.3 Ambient State

Ambient state is the state of external physical conditions that when acting singly or in combination on a given system can affect electrical and component states including but not limited to thermal, mechanical, and operational integrity under system duress.

2.3.1 Weather

Weather includes a variety of conditions affecting grid operations, such as ambient wet bulb and dry bulb temperatures, wind velocity, precipitation, fog (including salt fog), ice buildup, and humidity. Wind speed and direction can affect conductors somewhat, but are more of an issue when wind turbine generation assets are in play and can lead to system ramping events.

2.3.2 Other

2.3.2.1 Water Flow and Level

Water flow largely impacts generation, but in several ways: directly for generation via turbines, for cooling, and for use in generation used to balance wind generation.

- For generation: Run of river generators and tidal generators need water flow rates and profiles. Dam-based generators need seasonal flow information.
- For cooling: Thermal generators that use water for cooling (such as the once-through cooling used in some coastal generators) need water level, tidal, or seasonal flow information.

2.3.2.2 Insolation and Cloud Cover

Solar output in areas susceptible to cloud cover and insolation can be highly variable and contain high uncertainty for planning, forecasting, and balancing requirements.

2.3.2.3 Airborne Particulates

Particulate matter is a mix of small particles and liquid droplets. These particles can be made up of acids, organic chemicals, metal, dust, or soil. Generators using fossil fuels may emit various compounds into the air and natural conditions may cause airborne substances that impact grid operation.

3.0 Estimators, Modelers, Analytics, and Forecasters

Characteristics of the distribution grid that make it daunting for conventional analysis but ideal for application of advanced analytics are randomness of customer behavior, high nodal volume, lack of useful metadata and the number of unknowns such as grid topology and availability of behind-the-meter resources. In addition, the increasing number of sensors being deployed to monitor and help reliably manage the distribution grid produce constant streams of data. However, mere availability of more data will not, by itself, lead to changes in grid visibility, security, and resiliency. In order to create the predictive and prescriptive environment required for enablement of new markets and transactions for customer revenue and a reliable grid, the data must collected, organized, evaluated, and analyzed using sophisticated pattern-detection (i.e. incipient failure analysis can have subtle signatures only recognizable by advanced analytics) and discovery algorithms to provide actionable information allowing operators and customers to reliably manage an increasingly complex grid, and to enable progress toward scientific and engineering solutions for distribution grid challenges.

It is within this role that estimators, modelers, analytics and forecasting environments exist. Most states as outlined could be either inputs, or outputs of estimators, modelers, and forecasters, and utilized in the analytics realm to obtain full system observability, from both a past, present and future perspective These components will either utilize the state in calculation of another components state or predict the future of a particular state in a simulation type environment. These components can be both seen as utilizing states, or consuming the information of the state to produce useful actionable data.

An estimator in particular will utilize data driven analytics methods to calculate the state or future state of a component, based upon measured data.

A modeler will utilize measured data, and modeled data, representative of component states for example the modeled impedance of a conductor, along with voltage and current at two nodes, solved utilizing power flow analytics techniques, will produce the power flow and allow for evaluation of the possible constraint state.

Analytics form the backbone for the estimator and modeling techniques, but can also be considered as data driven, for example analytics would utilize a high fidelity measurement of current and voltage magnitude and phase angle state at a location on the distribution grid to determine if a power flow has changed direction during an unplanned topology change, or in the event of high penetration of DER at a substation.

Forecasters will predict the future state of a resource and often will be used as input to the estimator and modelers for more accurate future looking predictions.

A common system wide example to utilize here is the estimate of load, by which system operators such as CAISO[1] will determine the optimal generation profile – day ahead load forecasting for example. In this case the operators utilize analytics to determine within a given confidence level the load the following day and provide a new base state to which generators should be operating in the following time period. A second example is considering wind integration, where forecasted output based upon ambient conditions is utilized in the market for bidding capacity.

[1] California Independent System Operator

Appendix A

Outage Definition in the Presence of DER and Microgrids

Appendix A

Outage Definition in the Presence of DER and Microgrids

Traditional definition of a grid outage is a loss of electric power supply to an area. The net result of an outage is usually a lack of power for the consumer, or a set of mitigating strategies are taken.

As we evolve to a system where a customer being disconnected, or losing electric power supply from the utility owned electric grid is no longer directly linked to the lights being off, we must seek to redefine what an outage is. To consider this initially we must consider the definition of outage by which actor is subjected to it.

From the residential customers' point of view at present, the view of a traditional electric service is the presence of a utility electrical source, and in direct relation, a financial billing process, and unlimited supply of power for in home needs. Loss of such service is an outage. In the modernized grid this viewpoint must be altered. If we consider the future customer – one which may participate in services, or transact power with other local entity, an outage could represent an inability to generate power from their owned generation due to a state such as voltage being outside standard levels for inverter connections. The outage could also be driven by measurement of current or frequency by their local generation as outside standards for these technologies, meaning they lose revenue and local generating power, but in this case the lights would remain on and the consumer would continue to receive utility power.

An outage to the utility could also mean a local microgrid could provide local support, and desynchronize from the larger utility. In this case there is no traditional customer interruption in power, but there is a utility disconnect in place. In this scenario there can be a consumer wholly disconnected and not receiving utility power for a period of time. The utility is considered not serving the customer at this point, and the outage may still require rapid repair to ensure the customer can reconnect, but once again the customer does not lose power overall. The question would become more on ownership of the outage. If in this case the internal customer owned microgrid generation were to fail, there would then be a related lights out outage overall – more as seen in the traditional grid model at present.

For the larger bulk power system, which may in future consider clusters of DER as a large generator or supply point, the disconnection of these devices could be considered a generator outage, depending on the technology scheme in place to utilize the system. These types of "outages" are also considered contingencies. The loss of generation behind the meter in general and in bulk would likely be related to an overall loss of utility connection – therefore this could be considered as a lights out outage in addition.

An electrical outage therefore, may be a loss of capability to supply or absorb electricity, which may or may not result in a loss of actual electric power to consumer loads.

Appendix B

Electricity Markets

Appendix B

Electricity Markets

Figure B.1 shows the structure of US electricity markets (source: US Department of Energy Grid Modernization Initiative Grid Architecture Project).

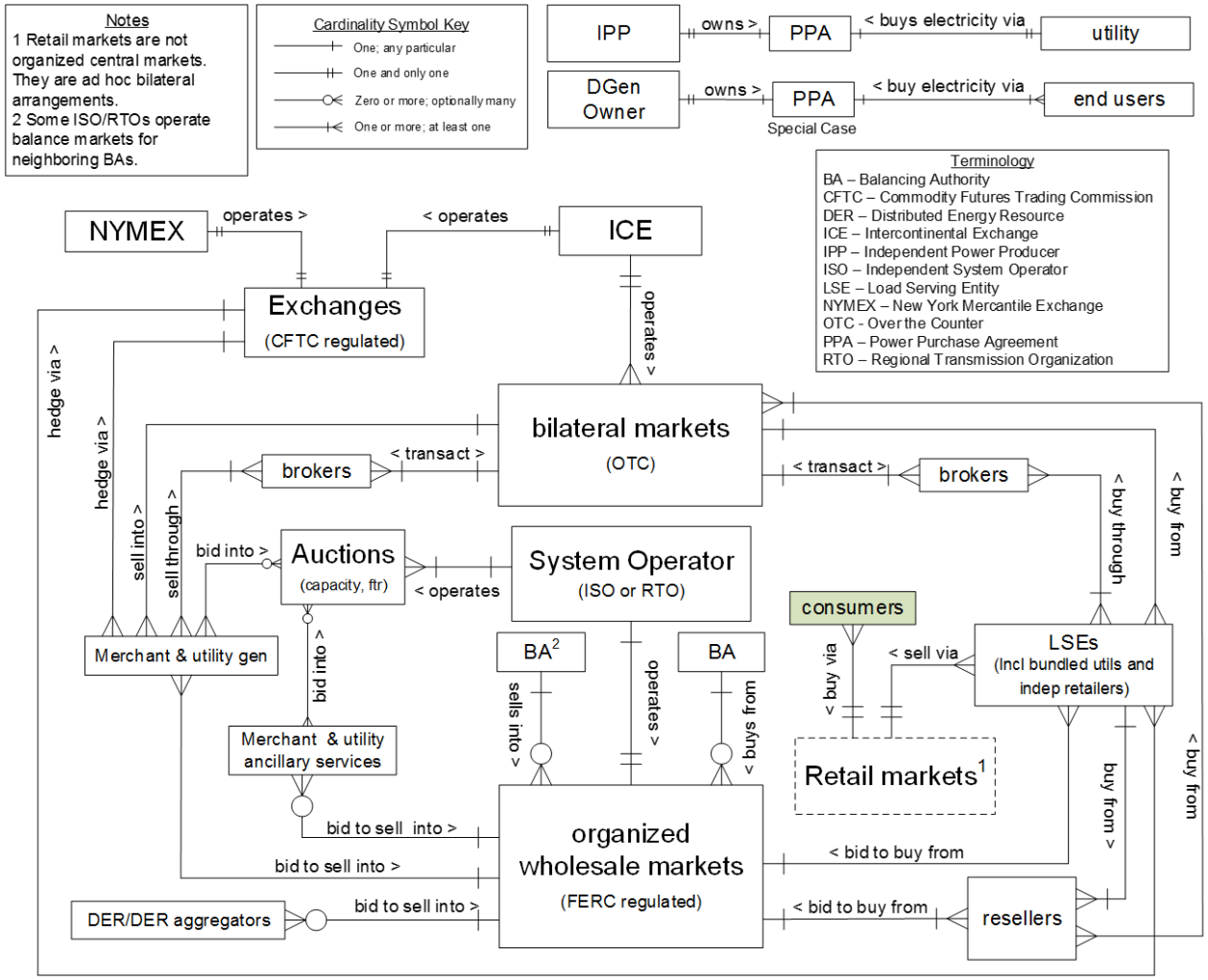

Figure B.1. US Electricity Market Structure

Figure B.2 shows the component model for US electricity markets (source: US Department of Energy Grid Modernization Initiative Grid Architecture Project).

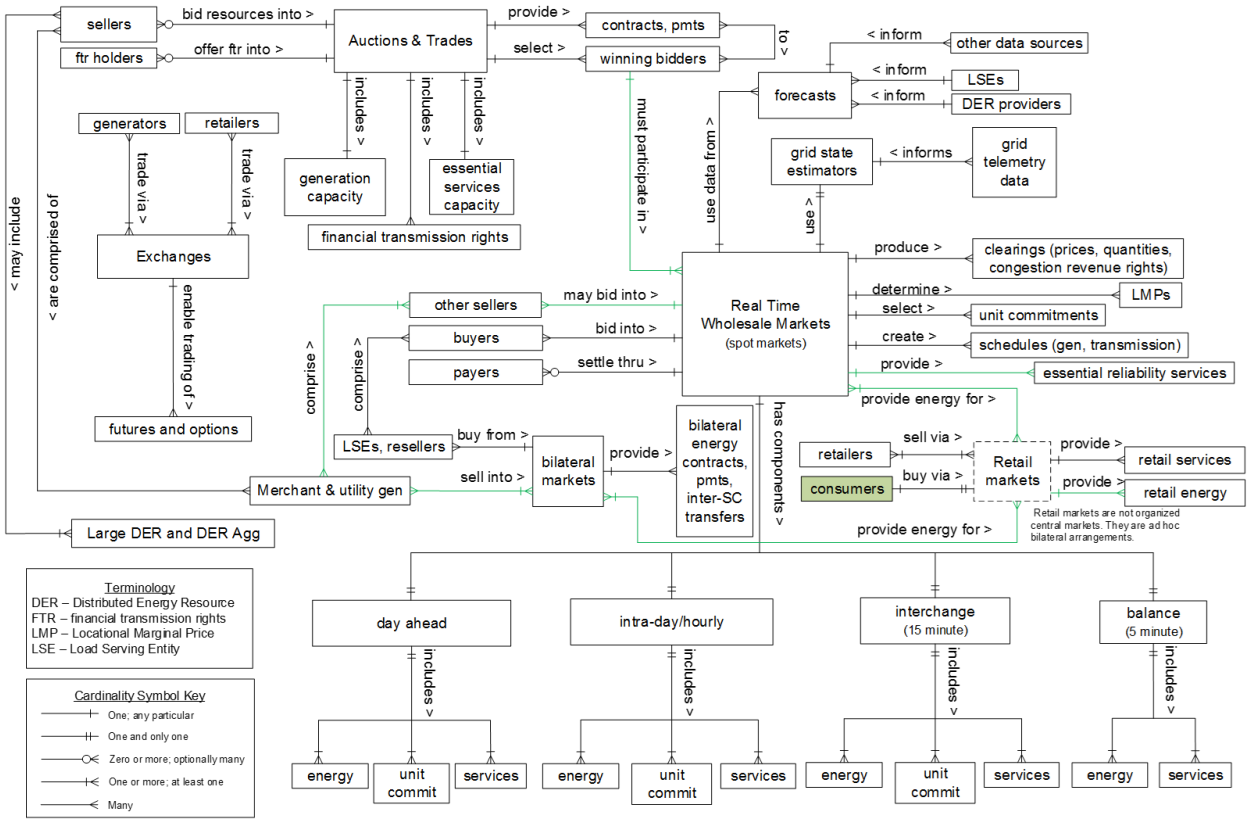

Figure B.2. US Electricity Market Components

Appendix C

Development and Validation

Appendix C

Development and Validation

This definition document was developed through a multi-stage process involving a core team from the US Department of Energy National Laboratories as part of the Sensing and Measurement Strategy project of the DOE's Grid Modernization Initiative Grid Modernization Laboratory Consortium program.

The project started with an initial version of the taxonomy diagram (v0) that had been developed as part of the original proposal process that led to the creation of the Sensing and Measurement Strategy project. The diagram and associated text went through a three-stage process of refinement, based on feedback from reviews at each stage plus work by the development team to stress test the definitions and taxonomy model. Version v3 is the final version and is presented in this document.

Stress testing by the development team consisted of two level of work:

- Conceptual analysis of the taxonomy and definitions by comparison against selected use cases, namely distribution level outage in the presence of DER, communication network operations, and asset stress monitoring.

- Web analysis, which consisted of graphical mapping of paths through the taxonomy to trace from the root to elements needed to support specific use cases.

Figure C.1 shows an example of the graphical web analysis done on an earlier version of the taxonomy.

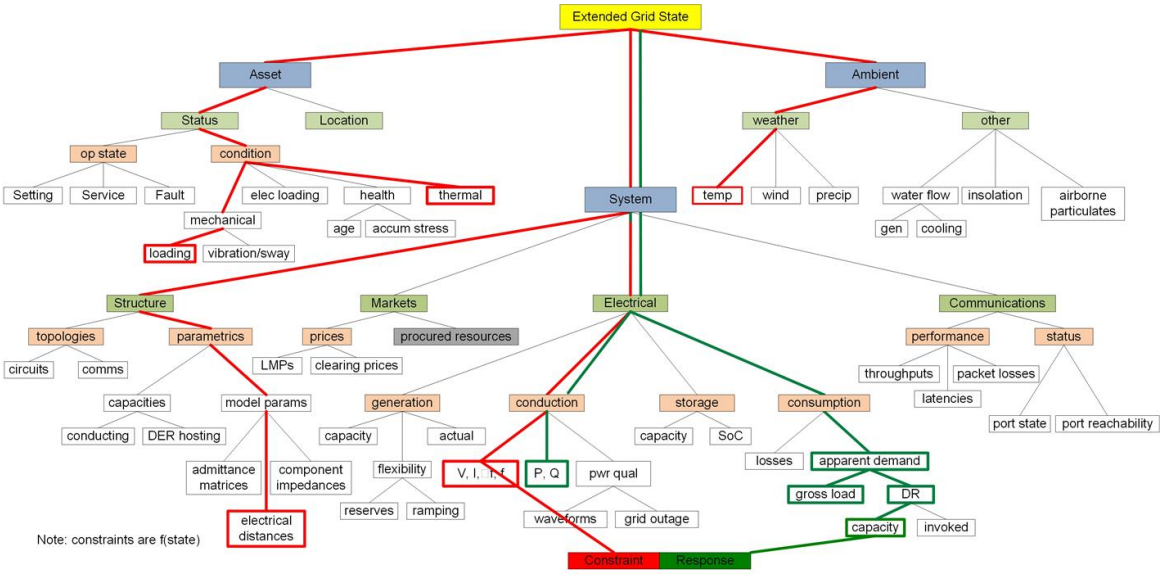

Figure C.1 Taxonomy Web Analysis Example Source: E. Stewart, LLNL

Reviews with experts external to the development team were used as the means to advance through three stages of model development. These stages are summarized in Table C.1.

Table C.1 Review Stages and Reviewer Types

Stage	Version transition	Reviewers
1	v0→ v1	non-team members of the National Labs
2	v1 → v2	utility industry (utility and vendor community) experts
3	v2 → v3	external organizations: • National Institute of Standards and Technology • North American Synchrophasor Initiative • Institute of Electrical and Electronics Engineers

The non-team members of the Labs were Lab experts who were not part of this project but who were subject matter experts of various kinds. The industry experts were drawn from an array of utility and vendor organizations and who participated in an online review under Chatham House rules to encourage open discussion. The third stage organizations were each contacted by the team to supply an expert who then reviewed the written materials and provided feedback independently of the others.

At each stage, the then current version of the taxonomy and text definitions was reviewed and the feedback captured from the reviews as addressed to update the document to the next version. Any additional considerations that had been identified by the development team were also addressed in the creation of the next version. An example of an issue that arose in the core team work was the question of how to define outage in the presence of Distributed Energy Resources. This led to the discussion in Appendix A of this document.

The development process also benefited from interaction with other GMLC projects, notably the Grid Architecture and Interoperability projects. That work includes clarification of various definitions used to characterize grids, one of which is observability, the subject of this definition document. Figure C.2 shows one of the definition models used in the Grid Architecture work that helped clarify the content of this definition document.

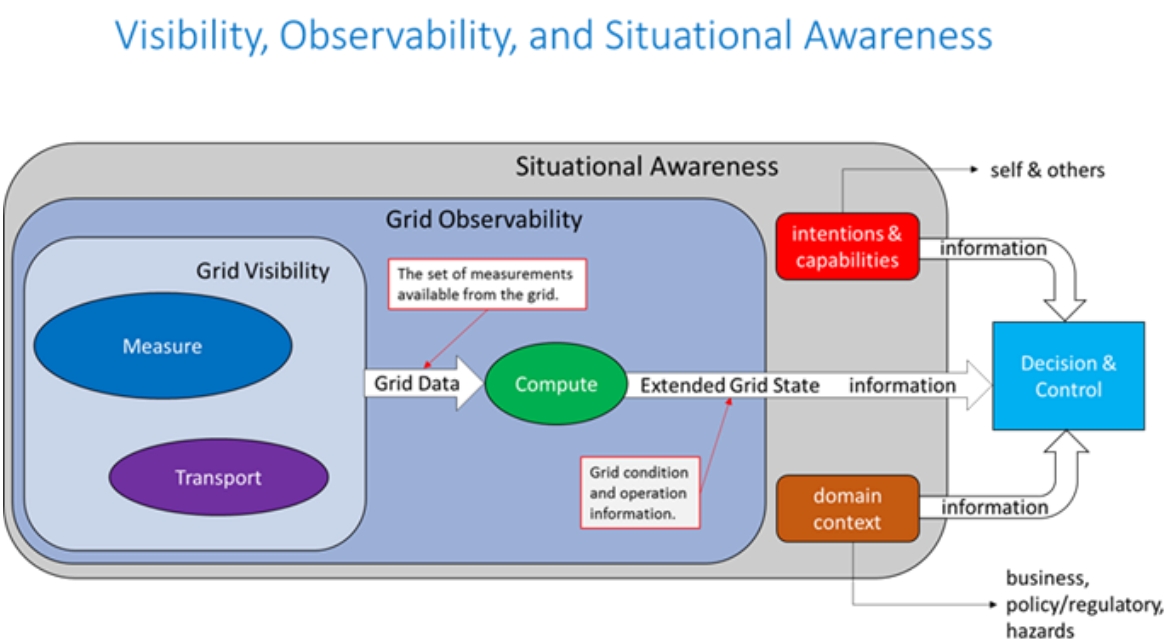

Figure C.2 Grid Architecture Definition Schema for Grid Observability source: J Taft, PNNL

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