PNNL-24463



# A Reference Model for Distribution Grid Control in the 21st Century

**July 2015 ver 1.1**

JD Taft
P De Martini
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

[1] Pacific Northwest National Laboratory
[2] California Independent System Operator
[3] California Institute of Technology

# Summary

Intensive changes in the structure of the grid due to the penetration of new technologies, coupled with changing societal needs are outpacing the capabilities of traditional grid control systems. The gap is widening at an accelerating rate with the biggest impacts occurring at the distribution level due to the widespread adoption of diverse distribution-connected energy resources (DER).[4] This paper outlines the emerging distribution grid control environment, defines the new distribution control problem, and provides a distribution control reference model. The reference model offers a schematic representation of the problem domain to inform development of system architecture and control solutions for the high-DER electric system.

[4] For control purposes, DER consists of Distributed Generation, Distributed Storage, and Demand Response.

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# 1.0 Grid Control Functions

Present day grid operation is based on several key principles: generation is centralized, connected at the transmission level and dispatchable; the grid has essentially no energy storage capability; distribution dynamics are slow and distribution can be treated as a fairly predictable passive load attached to transmission but not otherwise integrating with the bulk system. At the distribution level real power flow is one-way to the customer.

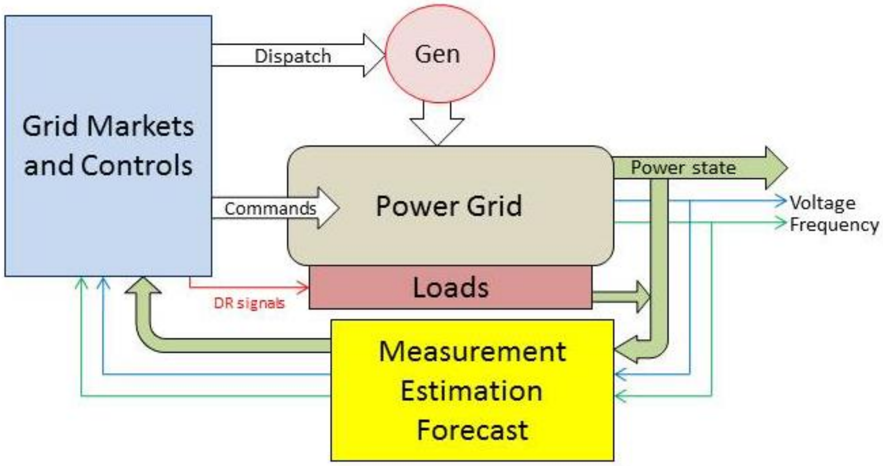
## 1.1 Types of Grid Control

Grid control is not a single function; it is a group of functions that can be classified into 12 categories. The categories, which include both bulk system and distribution functions, are listed in the table below.

**Table 1**. Grid Control Classes

| Control Type | Comments |
|---|---|
| Unit commitment | Daily on-off scheduling of generation units, usually on an economic optimization basis |
| Primary generator control | Internal control of generator power, frequency, and output voltage |
| Generator dispatch/scheduling | Hourly scheduling of generator power output on a day-ahead basis or intra-hour on a real time basis |
| Balance (and interchange) | Adjustment of generator power to follow load and maintain scheduled power exchanges with adjacent Balancing Authority Areas |
| Load sharing | Automatic adjustment of generator outputs to split load proportionately across a set of networked power generators; done via droop control at the transmission level |
| Power flow control | Direction of power flow in transmission and distribution circuits via switching, and via phase shifting transformers, power flow controllers, and variable frequency transformers |
| Regulation<br>• System frequency control<br>• Volt/VAr regulation | Feedback control to maintain a parameter at a set point. Two main types in power grids are frequency regulation via load frequency control, ancillary services and automatic generator control and voltage regulation (which usually also includes reactive power regulation) |
| Stabilization | Real time compensation for disturbances that can or would cause grid instability, e.g. damping inter-area oscillation |
| Synchronization | Adjusting AC phase (timing) to synchronize an AC generator or inverter with the (operating) grid |
| Direct load and DER control | Control of certain loads and DER by the utility via direct control commands, many in the form of net load reduction |
| Indirect DER management | Modulation of energy flows via signals or schedules that may include pricing or other indicators; the DER devices react via their own policies and so are not directly controlled |

The fundamental control paradigm for the 20th Century grid was dynamic balancing of generation and load in a load-following manner by dispatching generation, subject to limits on system frequency and voltage levels. In practice this meant control of grid **power state**.




## 1.2 Control/Market Interactions

At the bulk system level, ISO's and RTO's operate organized wholesale power and energy markets. Such markets have connections to bulk system control. Various kinds of market/control interactions exist[5] and in some cases, distribution level DER resources (most commonly DR) are bid into these markets and are dispatched by the ISO/RTO. At the time of this writing, distribution level markets do not exist in the US, but are being contemplated in several states, such as New York.[6]

## 1.3 Traditional Distribution Grid Control

Traditional distribution grid control was based on three functions: flow control, Volt/VAr regulation, and Demand Response. Flow control was accomplished through simple switching, most of which was manually directed. Voltage was controlled through regulators, and serial line drop compensators, some of which were automatic and some of which were manually adjusted. Reactive power was initially controlled (mostly by switching capacitors in and out of circuit) to perform support for voltage regulation. More recently, voltage and reactive power control became integrated, with optimization methods being applied to satisfy various objectives, including minimizing the number of voltage regulator operations in order to reduce maintenance problems. At present, Integrated Volt/VAr optimization is used for any of three objectives: simple voltage regulation, unity power factor control, and conservation voltage reduction. Automated solutions for Integrated Volt/VAr Control (IVVC) operate in both centralized and distributed forms. Distribution SCADA, where it exists, has a hub-and spoke structure, generally using communications networks owned by the utility itself.

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[5] Jeffrey D Taft, Lorenzo Kristov, Paul De Martini and Abhishek Somani, "Market/Control Interaction Models for Electric Power Grids," PNNL white paper.
[6] 14M-101: Reforming the Energy Vision, available online: http://www3.dps.ny.gov/W/PSCWeb.nsf/All/26BE8A93967E604785257CC40066B91A?OpenDocument

# 2.0 The Evolution of Distribution

A variety of forces are changing the requirements for grid operation. These include the increasing replacement of traditional generation at the bulk system level with non-dispatchable generation sources, especially wind and solar; the rapid penetration of generation (both dispatchable and non-dispatchable or "variable" resources (VER)) at the distribution level; the rise of "prosumers" (producer-consumers who can put energy back into the grid at the distribution level as well as take it from the grid); the emergence of microgrids and other local energy networks that can isolate themselves from the main grid and operate self-sufficiently for a time; the constant push to operate the grid for economy, thus driving reduction of operating margins originally established for reliability reasons; and the desires of customers to have choice in energy sources, to have transparency of energy usage information, and to have improved reliability and resilience in the face of natural and human stresses (including attacks) on the grid.

Some consequences of these changes are decreasing system inertia, growing volatility of generation sources, reduced predictability of distribution system behavior, and mismatch of generation and loads, leading to complications in managing grid power balance and stability. Fundamental changes in grid structure due to the rise of distributed generation, increasing speed of dynamic behavior of the distribution grid (too fast for human-in-the-loop operation), increasing need for high quality reliable, resilient power, and enormous increases in the complexity of the grid are all changing basic assumptions about grid control.

In response to the emerging trends and resulting systemic issues, electric distribution is being changed in a variety of ways. Overall, distribution is beginning to experience an evolution that will impact not just electric circuit technology, but also industry structure, business models, and regulation. This evolution varies, depending on utility type, geographic and demographic issues, and resource availability. Some large Investor Owned Utilities are considering a transition from being one-way power delivery channels to being N-way broad-access networks where any qualified entity can use the distribution network to carry out energy transactions with any other qualified connected entity and where buildings may become integral participants in real-time operations via pooling customer resources in order to seek access to different value streams. Others are considering emerging Distribution System Operator (DSO) models where the DSO manages all of the DER assets in its service area to meet its agreement with the ISO/RTO/Balancing Authority at an interface point such as an LMP node or Transmission/Distribution substation, while taking responsibility for safety and managing reliability in the distribution service area. Some of these models include operating as-yet undeveloped distribution level markets for DER and providing scheduling coordinator functions for economic transactions with ISO's and even providing micro-transaction clearing services.[7] Many co-ops have organized or are organizing into microgrids and may become networks of microgrids. Likewise, some communities are considering becoming microgrids or Local Energy Networks.[8]

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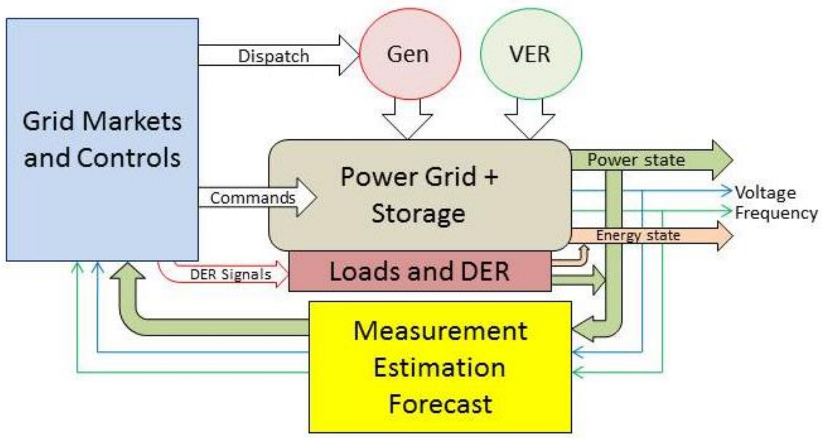
[7] Kristov and De Martini, 21st Century Electric Distribution System Operations, available online: http://resnick.caltech.edu/docs/21st.pdf

[8] See EPRI document http://smartgrid.epri.com/doc/IntelliGrid-Smarter-Transmission_Nov-2011.pdf

The evolving paradigm for grid control in the 21st Century is dynamic balancing of generation, load and DER in a hybrid source-and-load following manner by dispatching some generation, and using storage and load reduction, subject to bounds on system frequency, voltage levels, and DER capacities. In practice, this means control /coordination of grid **power state, energy state, and load state**.




While the implications for change are system-wide, the largest impacts are proving to be at the distribution level. The penetration of DER, combined with new capabilities for loads to be responsive to grid conditions is creating a rapidly changing environment for distribution grid control. These changes have also resulted in a re-assessment of the roles and responsibilities of the distribution service provider, and its relationship to the bulk system, especially in the ISO/RTO market environment.

# 3.0 New Distribution Grid Control Environment

The diagrams below illustrate a pair of views of a future distribution grid. Note that these diagrams are not an architecture and do not represent a solution design – they are depictions of a reference model that illustrates key aspects of the new distribution problem domain from a control point of view. Reference models are used in grid architecture work to depict problem domains from various points of view. In this case, distribution coordination and control is the relevant point of view.

Figure 1 below depicts a portion of a distribution system in which DER's of various kinds play significant roles. In addition to wind and solar generation sources, the model incorporates responsive loads, transactive buildings and a microgrid. It also contains three levels of storage: substation, neighborhood, and behind the meter. Power electronic flow control is depicted via inline flow controllers and solid state transformers but sectionalizing is via standard reclosers. Partial meshing of feeder primaries is depicted, with the inter-tie being a power flow controller instead of a switch. The feeder primaries are instrumented with line sensing and Volt/VAr regulation is done at various feeder locations.  Fast voltage stabilization is provided via power electronics at the feeder level.

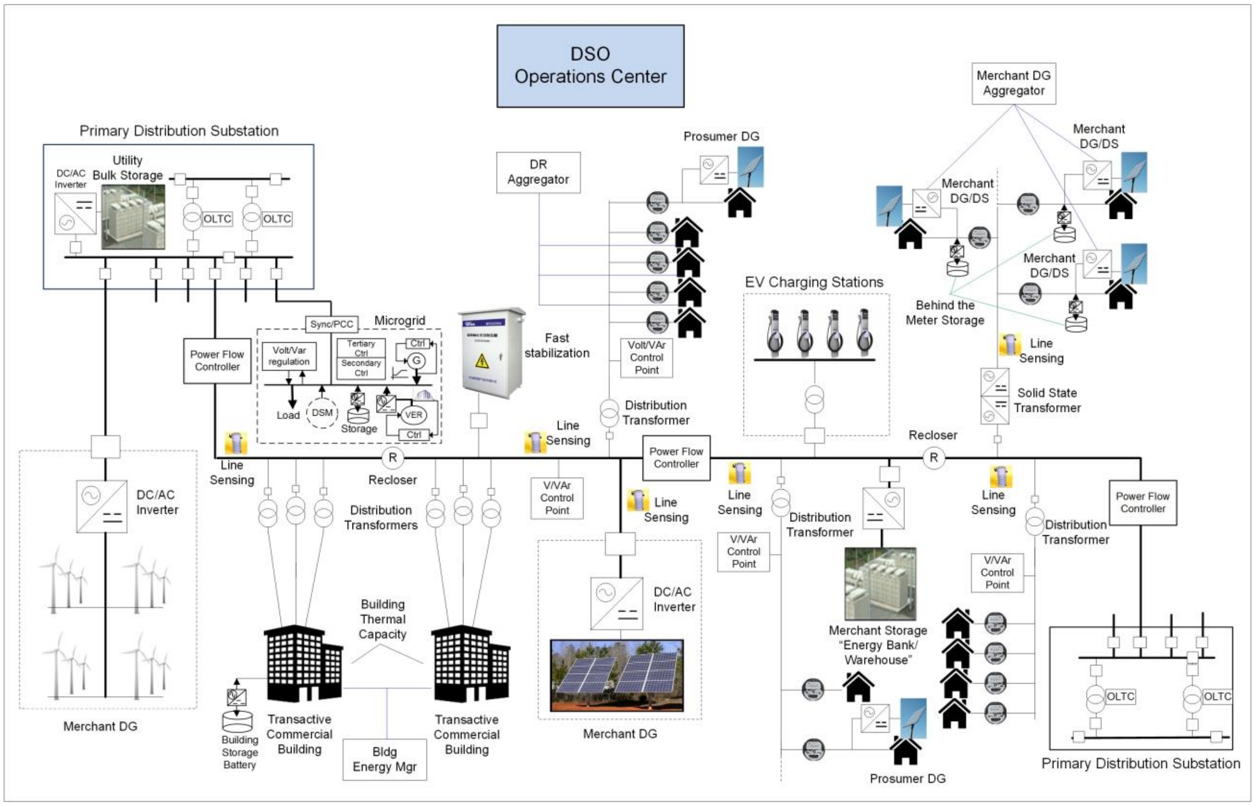



**Figure 1**.  Advanced Distribution Reference Model Physical Environment

The distribution system is managed by a Distribution System Operator (DSO). While there are a range of DSO models under consideration in the industry, this reference document presumes that the DSO has substantial responsibility for coordinating DER operation in its service territory and handles the interface to the bulk system Transmission System Operator at an LMP node or transmission/distribution substation.[9] Figure 2 below illustrates a general control environment for distribution under the scenario of large penetration of DER and consequent reorganization of the distribution service provider to incorporate the necessary DSO functional capabilities. Distribution service is provided by a combination of DSO and Distribution Owner (the entity that owns the distribution system assets and is typically responsible under state or federal law for their safe and reliable physical operation and maintenance). Note that in the short run, DER resources will continue to bid directly into ISO markets (dashed green line). Eventually, the scalability issues and reliability compromises inherent in this approach will result in all DER being bid through the DSO, even if some is intended for system support via the ISO markets. In that case, the dashed green line would not exist.

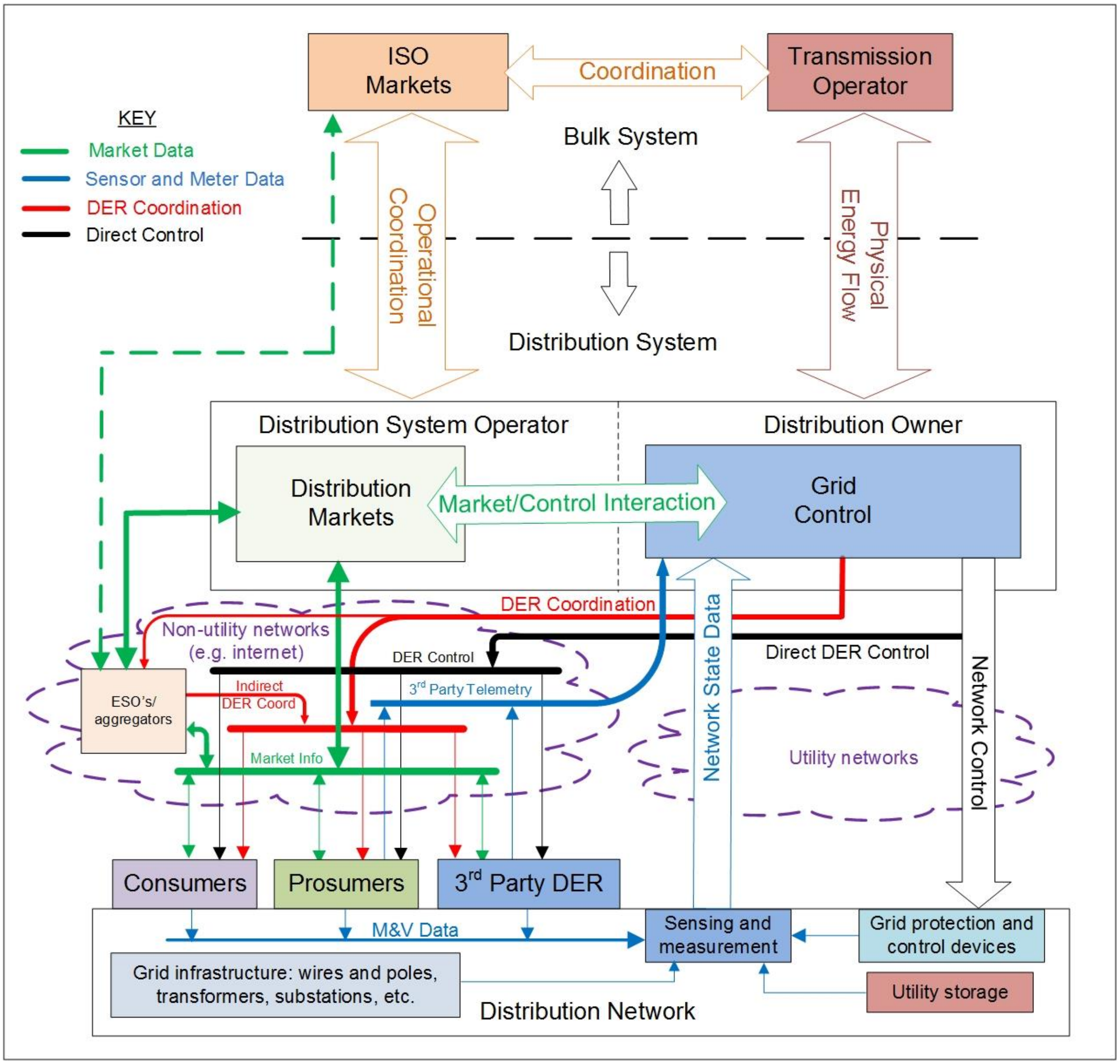



**Figure 2**. Advanced Distribution Reference Model Control Environment

[9] P. De Martini and L. Kristov, 2015 forthcoming, Distribution Systems in a High Distributed Energy Resources Future, Future Electric Utility Regulation Series, Lawrence Berkeley National Laboratory, pre-publication draft.

## 3.1 Multiplicity of Market, Sensing, and Control/Coordination Channels

In this environment, the DSO structure and the penetration of DER impact markets, control, measurement and verification, and communications profoundly. Key aspects of this model result in an increase in the number of channels through which the utility interacts with its consumers, prosumers, and merchant suppliers, which introduces new requirements for distribution control systems and communications networks.

### 3.1.1 Ownership of DER's

Four types of DER ownership are depicted in the model. Consumers may participate in Demand Response programs – these may comprise residential, commercial, and industrial facilities as well as microgrids (including transactive buildings). Prosumers may also provide Demand Response (or more generally Net Load Reduction via DR, DG and/or DS), as well as other power and energy services. Merchant and non-profit third party organizations (such as municipal utilities and Community Choice Aggregators[10]) will own DER (which may be installed at residential, commercial, or even industrial premises not owned by the third party) specifically intended for both customer load management as well as grid services or other energy or capacity value propositions. Finally, the Distribution Owner may own DG and/or DS components for use on their grids.

### 3.1.2 Communications Network Channels (purple clouds)

The future distribution model has two types of communication channels: the familiar utility network(s) that connect to grid devices, and non-utility networks such as the internet and other third party-owned networks (e.g., the Harris national fiber network). It will be necessary to connect via the internet because most DER assets will not connect through utility networks but will be routinely equipped with internet connectivity. These devices will in general have "Cloud" connectivity and in fact some useful services, such as aggregator services and analytics, will be provided by Energy Services Organizations (ESO's) via the Cloud in such a way as to appear seamless. Consequently, such services are depicted as part of the Cloud in Figure 2.

### 3.1.3 Market Access Paths (green lines)

DER assets can be bid into DSO markets either directly or via aggregators. In either case, the communication path is via the internet and Cloud. In one variant of the DSO model, DER may bid directly into the ISO market, individually or as elements of aggregated virtual resources, as shown by the dashed green line in the diagram. In another variant of the DSO model, that dashed green line does not exist and DER access to the ISO bulk markets is only through the DSO. In both cases the ISO's grid visibility extends only to the T-D interface. Therefore, although market bids, settlement-quality meter data and other financial information flow along the green lines, DER dispatch coordination does not (see Control and Coordination Paths below). Due to the need for dispatch coordination by the DSO/DO, a question for further consideration is whether the added coordination challenges of allowing direct DER participation in the wholesale market (dashed green line) is outweighed by the benefits.

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[10] CCA's are direct access providers created by city or county governments for their areas that utilize an Investor Owned Utility distribution system.

### 3.1.4 Control and Coordination Paths (red and black lines)

In the model, there are two different paths for DER coordination (in red), one path for direct DER control (in black), and another path for standard grid control. The three DER paths make use of the internet for communications because that is how the non-utility DER assets are connected. Two are coordination paths: one for direct coordination of DER by the DSO, and one for indirect coordination via an aggregator. The third path is for direct control of DER by the DO portion of the utility. An example would be command of DG or DS inverters for reactive power control. This form of control resembles traditional grid control but the assets being controlled do not belong to the utility and do not have utility network connectivity.

The fourth path for traditional grid control makes use of standard utility networks. It is possible that some DO's will employ the internet or other public shared networks (such as municipal Wi-Fi), but even so, all four paths will still act as independent virtual private networks for security purposes regardless of how the physical networks are arranged.

### 3.1.5 Sensing and Measurement Paths (blue lines)

Sensing and measurement data will arise for three distinct classes of sources: grid sensors and devices, meters, and DER devices and systems. Grid power state and energy state data will be collected in the usual manner, via SCADA and utility network(s). This includes meter data for both billing and DER measurement and verification. Given the complications that DER may cause on a distribution grid, distribution sensing will require somewhat sophisticated observability strategies, may include new kinds of sensors, and will certainly involve much greater data volumes and rates.

In addition to utility-owned sensors, DO's will use data from the instrumentation incorporated in DER devices. Such telemetry will travel via the internet and Cloud, so that network state data will arrive at the DO through two possibly distinct channels (internet/Cloud and utility networks).

### 3.1.6 Additional Depictions

Appendix A shows a depiction of the present day model for distribution control with DER in an ISO/RTO environment.

Appendix B shows a mapping of core DSO/DO functions onto the diagram of Figure 2..

## 3.2 The Mixed DER Control Problem

The coordination of a mixed set of DER's (DG, DS, and DR) presents a nuanced control problem. In some instances, diverse DER types may exist in a local area simply as a result of implementation by customers and third parties; in other instances, an aggregator may formulate a virtual resource comprised of diverse DER types. These assets are capable of providing four classes of control effects to the grid, but not with uniform capability. The four types of DER control effects are:

- Energy Supply – providing energy into the grid
- Net Load Reduction – reducing demand or supplying supplemental energy behind the meter
- Reactive Power Control – providing leading or lagging power to the grid
- Energy Absorption – collecting and storing energy from the grid.

The mapping from DER types to DER control effects is shown in Figure 3.

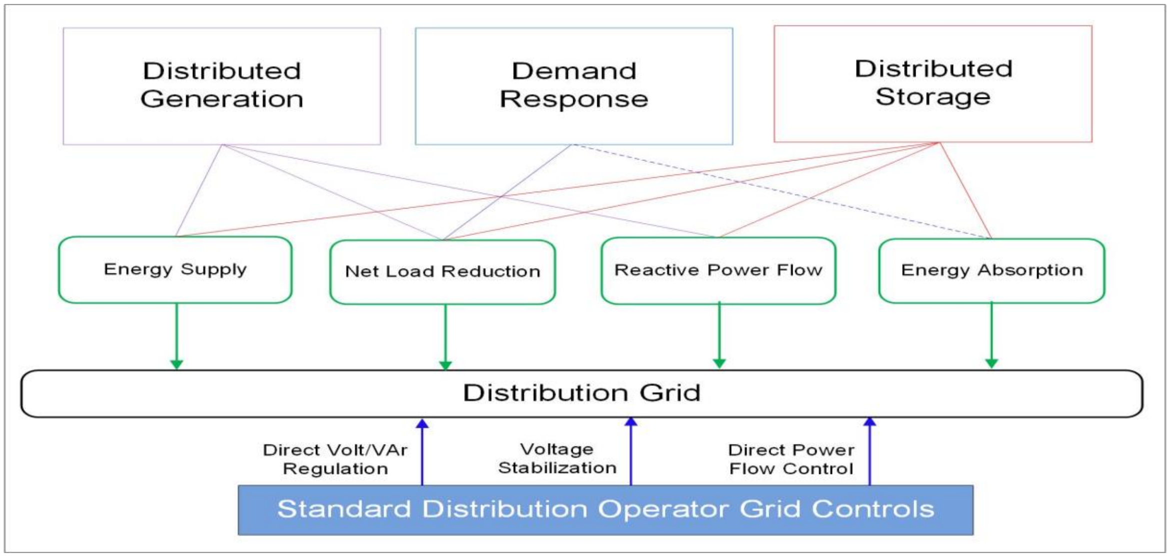


**Figure 3**. Mixed DER Control Mapping

As the figure indicates, DER assets do not supply uniform support for DER control effects. What the diagram does not show is that there are additional constraints for specific DER's that are dependent individual implementations. Table 2 describes some characteristics of the control effects of various DER types.

Table 2**. DER Control Effects Analysis**

| | **Distributed Generation** | **Demand Response** | **Distributed Storage** |
|---|---|---|---|
| **Energy Supply** | By definition, but some are dispatchable and some are stochastic | No | Bilateral storage can supply energy until depleted; certain forms of storage cannot provide electric output (e.g. building thermal storage) |
| **Net Load Reduction** | At multiple scales when acting as per circuit laws only: behind the meter; behind the service transformer; behind the substation | By definition | At multiple scales (behind the meter; behind the service transformer; behind the substation) acting as per circuit laws until storage is depleted |
| **Reactive Power Flow** | Using controllable inverter | No | Using controllable inverter if storage is bilateral |
| **Energy Absorption** | No | Can mimic this function by releasing load already under DR as long as the load is immediately called for at its site; however it cannot release the "stored" energy back to the grid | By definition<br><br>Note that some forms of storage do not provide electricity back to the grid (e.g. building thermal storage) |

Several "compound" control effects have been defined or at least imagined. These are combinations of the four basic control effects listed above. For example, storage could provide synthetic grid inertia, but this would require both energy supply and absorption acting in a very fast (sub-second) bilateral manner (electric energy both in and out of storage) which not all forms of storage can do. Similarly, temporal energy shifting could be accomplished by timed use of net load reduction. While direct voltage regulation is not shown in the figure and table above, DG and DS could provide some capability but IEEE 1547 (at least for now) excludes this function.

### 3.2.1 Temporal/Locational Value

At the bulk system level, DER's can exhibit limited locational value. At the distribution level however, every DER has locational impact, which may be an advantage or a disadvantage, depending on various factors. As with all distribution level data and control actions, circuit topology is the context in which meaning and functional value are determined. Distribution topology can be time-varying on both fast and slow time scales, challenging the ability to maintain correct system models at all times. One of the consequences of this is that a DER value determined via a market operation at time $T_1$ may have degraded or become problematic or incorrectly evaluated at later time $T_2$ due to circuit switching in between times $T_1$ and $T_2$. For DER's that are bid into wholesale markets especially via aggregators (because for the most part markets or other revenue opportunities for distribution-level services don't exist yet), locational impact will complicate the distribution control problem and there will be a challenge for such aggregations at the bulk or distribution levels to quantify performance characteristics so as to incorporate them into dispatches in optimal or even adequate ways.

The value of DER's also varies with grid state and so exhibits rapid temporal and locational value variations. Some DER's may have value in relieving circuit congestion, but this value may only apply during a relatively small number (50-60) of events per year and be highly dependent on location and capability type (control effect). In addition, the determination of distribution level congestion on real time or near real time scales requires distribution sensing and software tools that do not presently exist.
DER value also depends on the presence of other DER. Consider the effective merit seen by the distribution utility of neighborhood scale storage as compared to DR for that same neighborhood, keeping in mind not only control effects, but additional factors such as resilience. Also consider the value of an ensemble of stationary DER in the occasional presence of storage in the form of electric vehicles, or on a longer time scale, when new DER's are installed by non-utility entities where DER's are already dense.

### 3.2.2 Energy State Control

For distribution level energy storage owned and operated by the distribution utility or by third party suppliers (but not behind the meter), a key issue is the management of energy state (state of charge). Bilaterally fast storage is capable of supplying many capabilities, many of which can be supplied simultaneously.[11] Such storage has multiple potential values, including in relation to issues of grid reliability and resilience. In this light, storage offers opportunities for functions analogous to gas "line packing" in advance of severe weather as well as energy banking/warehousing and other value stream innovations yet to be defined. To make this work though, it will be necessary to manage battery charge states in a dynamic manner for system purposes beyond simple power flow management.

[11] "Grid Architecture," U.S. Department of Energy, January 2015, available online: http://energy.gov/epsa/downloads/grid-architecture

DER dispatch will be a complex function of DER type, grid location and topology, power and energy state, and electrical proximity to other DER's, in addition to cost. A combination of distribution market mechanisms and distribution level Optimal Power Flow (OPF) or its distributed equivalent may be required to realize the full potential of DER's. As with many electric system issues, various simplifications may ultimately be applied.

## 3.3 Other Distribution Issues

### 3.3.1 Volt/VAr Regulation and Stabilization in Partial Meshes with DER

Traditional distribution feeder Volt/VAr regulation systems expect only slow dynamics, but in a partially meshed high DER penetration environment that condition would not apply. There have been suggestions that solar inverters could participate in feeder regulation and could do so via participation in some form of spot market. Given sub-minute but even sub-second dynamics due to feeder switching and flow control, fluctuations due to stochastic generation such as wind and solar, and interactions with responsive loads, regulation and stabilization of voltage and reactive power will need to operate on very fast time scales (as fast as sub-cycle).

### 3.3.2 Load Sharing for DG and DS

The load sharing problem at the bulk system level is solved using local droop control on the generators and the electro-mechanical interactions of generators through the transmission grid. No supervisory controls or communications from generator to generator are used. The load sharing problem had not been an issue at the distribution level until significant levels of DG penetration began to occur. If the future of distribution includes significant amounts of DG and DS that are not acting solely as behind the meter net load reduction but are providing scheduled energy transactions, then the load sharing problem will exist at the distribution level. Various researchers have worked on load sharing solutions for DG, but products do not exist and standards such as IEEE 1547 will need to be revised before the problem can be considered solved.

### 3.3.3 Broad Access Networks

Given the changing model for distribution operations, some utilities are considering changing their operational models from being one-way delivery channels to being openly accessible networks for energy transactions. For this to work, it is not sufficient to have a set of interface definitions and interoperability standards. It is necessary to have a coordination framework that admits new properly authorized devices to the network without intervention for configuration purposes and also handles device disconnection the same way. Such a framework must fully integrate the new device into the operational processes, including market processes if they exist.

# 4.0 Conclusions

Electric distribution is changing in many part of the US. The penetration of DER, combined with expansion of responsive loads and increasing consumer expectations, has caused a reconsideration of the basic environment in which distribution control operates. This paper has outlined a new reference model for distribution system control and has described the new control problem and key requirements. The new reference model recognizes that grid control must encompass many assets not owned by the utility and correspondingly cannot rely solely upon grid data sources and communication channels. This in itself has implications for the design of advanced Distribution Management Systems, both in terms of capabilities and cyber security.

The distribution grid control and coordination problem itself is changing rapidly and the gap between traditional distribution grid control and the requirements of the newly evolving environment is widening rapidly. The potential presence of a mix of DER elements poses a new kind of control/coordination opportunity with as-yet unresolved complications. In addition, if some form of distribution level market mechanism is employed, the interactions between the market and the control/coordination mechanisms must also be considered, which adds another new dimension to Distribution Management System design. Locational value and locational density create considerations for the DER dispatch problem that do not have simple counterparts at the bulk system level, and the presence of aggregators can mask some of the locational characteristics of DER's, further complicating the problem of realizing best value from DER investments.

In this evolving environment, it is crucial that the control problem be framed properly and this means not just as a set of siloed applications, but as a *whole problem formulation* in the context of a complete reference model and corresponding architecture.

# Appendix A

# Appendix A

Diagram A.1 provides a depiction of the present day as-is model for distribution control with DER in an ISO market environment. Note that the ISO may have a DR program that treats DR in a manner similar to generation and at the same time distribution utilities in the same Balancing Authority Area may also have more localized DR programs.

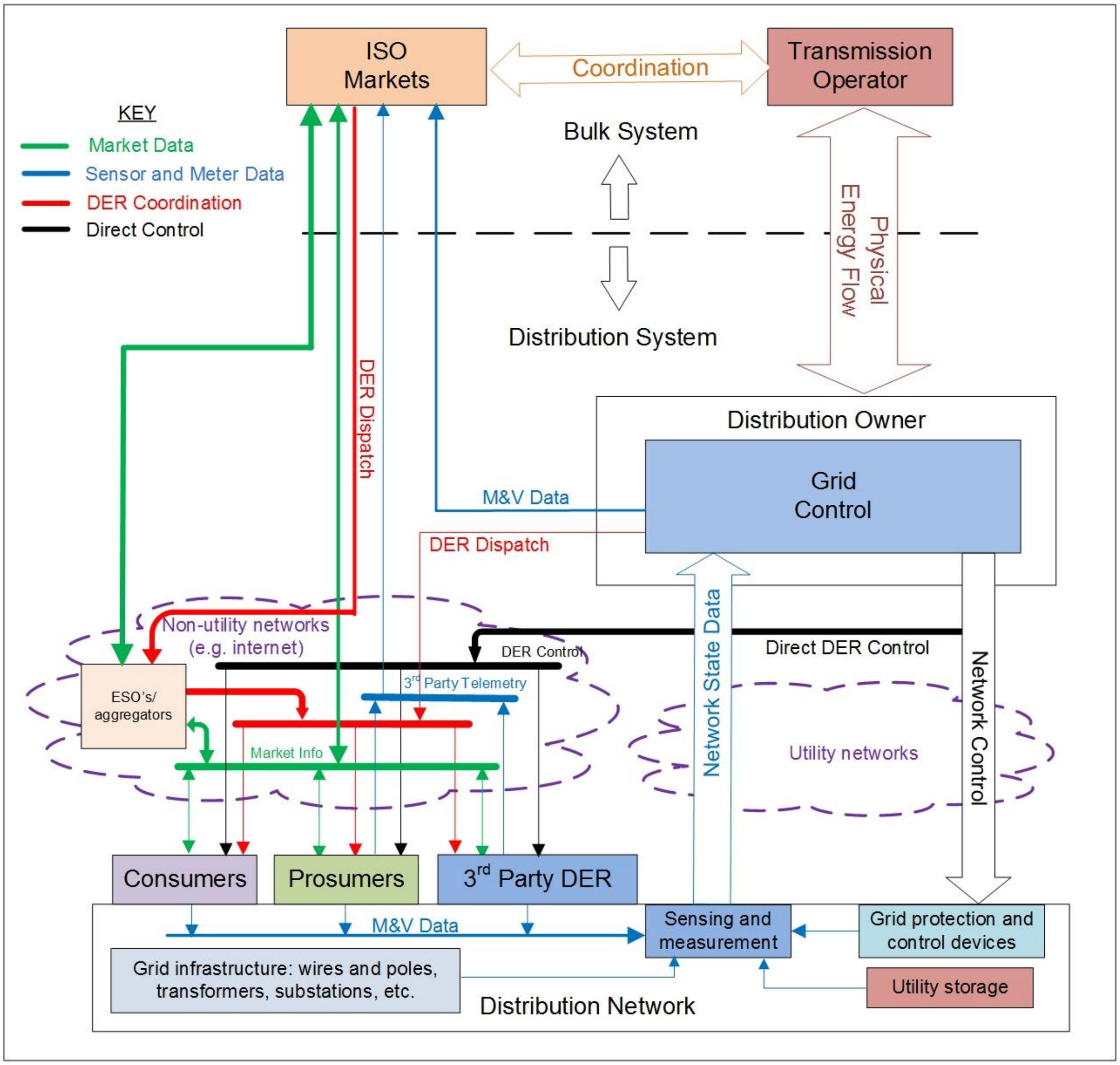


**Figure A.1**. Present Day Distribution Control Model with DER in ISO Market Environment

# Appendix B

# Appendix B

Diagram B.1 below provides a mapping of key DSO/DO functions onto the future control reference model diagram of Figure 2 above. The function set is derived from recent work on DSO model definitions.[12]

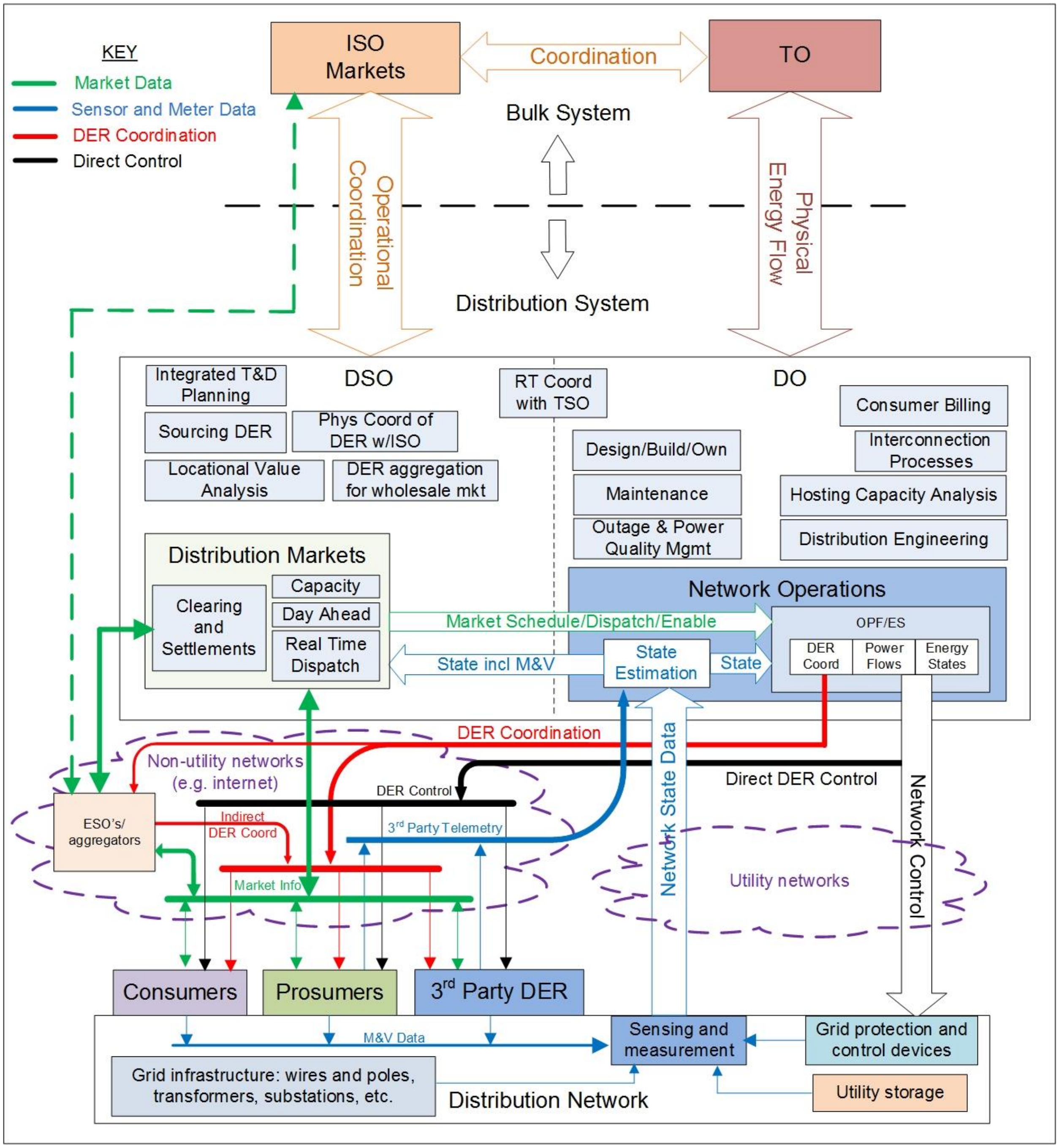


**Figure B.1**. Reference Model with Core Function Mapping

[12] Paul De Martini and Lorenzo Kristov, "Distribution Systems in a High Distributed Energy Resources Future," Future Electric Utility Regulation series, Lawrence Berkeley National Laboratory, 2015 forthcoming.

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