21st Century Electric Distribution System Operations

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Introduction

The electric industry has gone through dramatic changes over the past two decades. The restructuring program begun in the early 1990s opened up the wholesale markets with numerous competitive generation companies transacting over open-access transmission systems. New entities called independent system operators (ISOs) and regional transmission organizations (RTOs) arose as wholesale market operators and transmission service providers for the majority of customers in the US. In other locales, traditional utility balancing authorities evolved to provide similar functions for their area of responsibility. Many states also opened retail electricity supply to competition, allowing customers greater choice over the sources of energy and creating new business opportunities for retail providers. Concurrently, over 40 states enacted policies to promote renewable supply portfolios and a similar number have net energy metering tariffs which have helped to spur adoption of distribution energy technologies. All of this has occurred during a period of increasing customer service and reliability expectations. Combined, these factors are creating a need to transition our electric system into a 21st century power system that continues to be reliable and cost effective while incorporating more sustainable energy sources.

Through all the above changes, two fundamental features of electric service hardly changed at all: the predominant flow of electric power in one direction only, from central station generators over wires to end-use customers, and the fact that electricity can't be stored in any significant quantities. Both of these features are now beginning to change rapidly, and expectations across the industry are that these trends will accelerate in the years to come. These changes require a fundamental rethinking of operational and infrastructure-design aspects of power systems to a much greater degree than was necessary to accommodate the changes of the last two decades. In particular, distribution systems that have traditionally operated passively to move electricity from the high-voltage transmission grid to end-use customers were never designed for bi-directional flows that could originate from any point on the system and from any one of dozens of different types of distributed energy resources (DER). Also, distribution system operations were not designed to integrate or coordinate thousands of flexible customer and merchant DER or micro-grids capable of seamless islanding.[2] As such, the time is now to consider the core functions, roles and responsibilities necessary to reliably operate an efficient and increasingly distributed power system.

We introduce the term **integrated distributed electricity system** to denote the new structure, to recognize that energy sources and operating decisions will be broadly decentralized and localized, while customers, micro-grids and larger DER continue to benefit from connections to the transmission grid

[1] **Ideas presented in this paper are for discussion purposes only and do not reflect the views or policies of the California ISO.**

[2] P. De Martini, N. Fromer and M. Chandy, Grid 2020:Towards a Policy of Renewable and Distributed Energy Resources, Caltech Resnick Institute, 2012

and wholesale market operated by Balancing Authorities (BAs) such as the CAISO, an RTO or a traditional integrated utility transmission operator. Figure 1 provides a conceptual schematic view of the emerging integrated distributed structure.

Although it is important to take a whole-system perspective, the authors see an immediate need to focus first on the physical operation and architecture of the basic building block of the new power system, namely, the set of distribution facilities that radiate from each transmission-distribution interface point, plus the DER and customers connected to those facilities.[3] For discussion purposes we will refer to this building block as a **local distribution area** that will be operated by a **distribution system operator** (DSO) as discussed below (represented by each triangle labeled "DSO" in Figure 1).

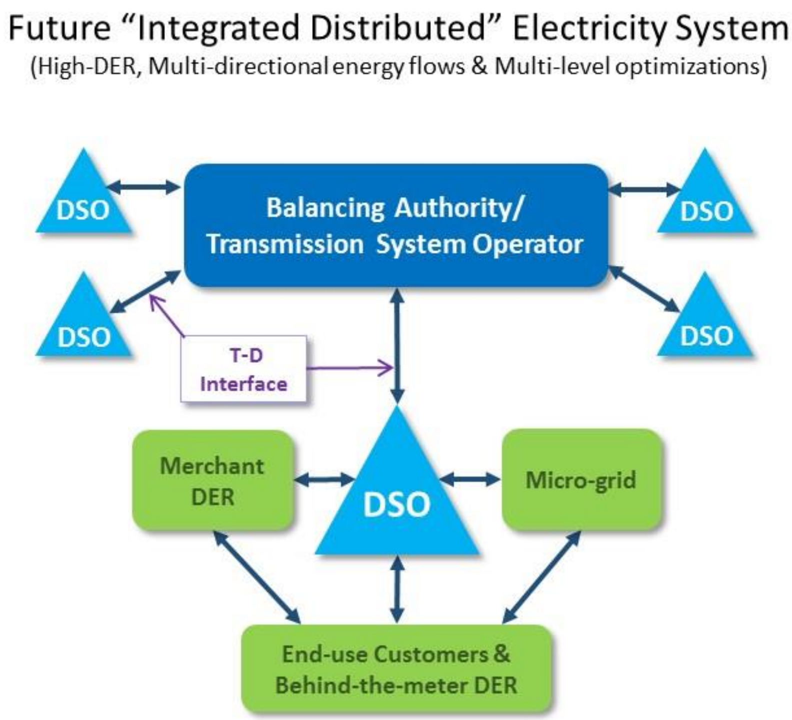

Figure 1: Integrated Distributed Electricity System

The information and system control architectural structure implied by this diagram is an example of what has been described as "constraints that de-constrain."[4] By specifying the structure implied here, a variety of design issues involving control and coordination mechanisms, networking, data management, and operational systems design are substantially simplified. This also eliminates the "tier hopping" that has been identified as a significant fatal flaw in current practice.[5] Finally, this structure should minimize

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[3] Typically this interface point is a substation linking a set of radial distribution circuits to the high-voltage transmission network. In organized markets using the locational marginal pricing (LMP) market paradigm, the transmission-distribution interface substation is a pricing point, often called a "Pricing Node" or "P-node."

[4] Steven Low, Caltech, EPCC Workshop presentation: http://www.epcc-workshop.net/assets/downloads/low-presentation-control-arch-ders.pdf

[5] The power system has three basic control system tiers: bulk power system, distribution system and customer system. Tier hopping is the practice of directly linking the controls of one tier to that of a tier two levels away. That is, skipping the adjacent tier. For example, directly connecting bulk power system controls to customer systems, bypassing distribution

the potential impact on legacy BA, ISO and RTO systems enabling a more graceful evolution of operations and lower costs to implement.

This paper offers an initial contribution toward developing a practical model of local distribution area operation and architecture. To make this complex and nuanced problem as tractable as possible, we start from a few basic modeling assumptions and strategies:

1. A single local distribution area consists of all the distribution facilities and connected DER and customers below a single T-D interface on the transmission grid, and is not electrically connected to the facilities below another T-D interface except through the transmission grid.
2. The starting point of the inquiry is the operation of the local distribution area, including all activities required to maintain safe, reliable, efficient distribution service to customers and connected DER, as well as a stable interface with the transmission grid.
3. A single entity operates each local distribution area and is responsible for providing reliable real-time distribution service. We refer to this entity as a **distribution system operator** (DSO).

   Our strategy is to start by identifying the minimal set of functions the DSO must perform to fulfill its core responsibilities. We expect the core functions of such a "**Minimal DSO**" to have the characteristics of a natural monopoly, and to be a natural extension of today's utility distribution company (UDC) system operations with the appropriate separation between grid operations and any retail energy sales and services.
4. After describing the Minimal DSO functions, we will consider future services the DSO might offer beyond the minimal, without yet exploring the question of which industry participants might provide these services.
5. The operational requirements of the DSO will drive the design of the physical and information architecture needed to support the integrated distributed industry structure. In particular, we expect the effort sketched in this paper to be a useful input to subsequent efforts to develop new distribution system infrastructure.

Clearly the above assumptions and strategies exclude many important and interesting questions. Those questions are only temporarily deferred, however, not ignored. Having dealt for many years with complex matters of electric industry structure, system operation, market design, infrastructure planning, and so on, the authors have come to recognize that systemic changes must be approached through a combination of bottom-up and top-down thinking. The integrated distributed electricity system model illustrated in Figure 1 provides an initial top-down view of where industry evolution is heading. But to arrive at a whole-system design that works effectively in practice we must specify the details of the constituent bottom-up building blocks in enough detail to ensure they will work effectively in practice.

Foundational Concepts and the Distribution System Operator

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system controls such as wholesale "prices to devices". This will lead to detrimental service quality on distribution and will cause system instability if used in large scale.

The envisioned **Integrated Distributed Electricity System**[6] is characterized by a complementary mix of centralized and distributed resources including generation, energy storage, power flow and stability control devices, and control systems including sensing devices and load management capabilities. These resources are owned and controlled by a number of parties, including utilities, merchant distributed generators, merchant energy storage, demand aggregators, energy services firms[7] and customers. To provide safe and reliable electric service, such a system requires an integrated and coordinated operational paradigm that clearly delineates roles and responsibilities between the transmission system operator (TSO)[8] and distribution system operators.

The fundamental TSO role and responsibility remains to provide reliable open-access transmission service. This entails maintaining supply-demand balance and transmission reliability by scheduling and dispatching resources and interchange transactions with other regional balancing authorities. The new challenge for the TSO arises from the need to consider the increasingly dynamic net load and high penetration of flexible DER across the T-D interface at a substation.[9]

Traditionally, the UDC maintained safety and reliability of the local distribution system (including non-FERC jurisdictional sub-transmission facilities) within an operating regime where power flowed almost entirely one way, from the transmission grid to end-use customers. This involved regular reconfiguration or switching of circuits and substation loading for scheduled maintenance, and to isolate substation and distribution feeder faults and restore electric service. This “fault location isolation and service restoration” (FLISR) activity is partially automated but most of the switching required is not. UDCs are also responsible to ensure local voltage, power factor and phase balance[10] are maintained within engineering standards.

With a greater number of DER, the potential for multi-directional power flows across the distribution system has emerged and is likely to become prevalent. In addition, as independent micro-grids develop and electrical standards allow seamless islanding, system operations will need to include coordination of DER and micro-grid operation and interconnections. This also includes coordination between the DSO and its TSO counterpart on the other side of the T-D interface.

Thus, in addition to the functions performed by the traditional UDC, the DSO will be defined by a new minimal set of functional responsibilities. This includes reliably operating the local distribution system below each substation, which will entail coordinating operations of the interconnected DER, micro-grids and self-optimizing customers, and scheduling interchange with the TSO at the T-D interface. Although these changes will make distribution system operation much more complex than it has been in the past, they appear to reflect the direction public policy, customer preferences and technology are taking the industry. And if the new operational requirements are designed and managed well, the changes can be broadly beneficial to energy customers and the economy as a whole.

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6 Staff, The Integrated Grid, Electric Power Research Institute, February 2014

7 Includes traditional energy services firms such as ESCOs, energy retailers and solar PV services firms.

8 Includes Balancing Authorities such as utilities, Independent System Operators and Regional Transmission Organizations (ISO/RTO).

9 For those regions with organized wholesale markets, the T-D interface may be a locational marginal pricing node (“P-node”).

10 Distribution circuits do not typically operate balanced across all three phases, unlike transmission lines. This is due to most customers and their DER being connected to the secondary side of a single phase secondary transformer. There are, however, limits to the amount of phase unbalance that can be tolerated.

Another way of thinking about the integrated distributed electricity system is through the concept of **Distributed Reliability.** This concept refers to a federated reliability paradigm in which DSOs, and potentially micro-grids[11] and self-optimizing customers – enabled by diverse small-scale generation, energy storage, power flow control devices, demand response and other DER combined with advanced information and control technologies – have responsibility and accountability for the reliable real-time operation of the respective electric systems under their operational control. Elements of this federated system may adopt islanding capability to enhance "local resilience" to maintain electric service under stress conditions on other parts of the electric system. Such a system requires integrated operational processes and distributed control systems to ensure reliability.[12,13]

Underlying the distributed reliability concept is the recognition that many types of DER and independent micro-grids will be capable of providing **Distributed Reliability Services** to support reliable real-time distribution system operations**.** Such services will be provided by diverse DER, according to their performance characteristics and capabilities, to the local distribution system to which they are connected. These services may be provided to the DSO via tariffs, bilateral contracts or other means, to enable the DSO to reliably operate the distribution system and manage variability at the T-D interface, and may also be provided to other entities across the distribution system, such as municipal utilities. The DSO's ability to use locally-provided reliability services will enable it to maintain a more stable and predictable interchange with the TSO at the T-D interface, thereby relying less on the TSO to provide energy balancing and other real-time services, and even utilizing DER with appropriate performance capabilities to provide such services to the TSO.

Another required DSO function as a natural extension of the above is **T-D Interface Reliability Coordination.** This function is to ensure that DER-provided services are properly coordinated, scheduled and managed in real-time so that the TSO has predictability and assurance that DER committed to provide transmission services will actually deliver those services across the distribution system to the T-D interface. The DSO must ensure that the DER providing reliability services don't have any conflicting service commitments, such as offering the same capacity to serve both the TSO and the DSO or another entity. This coordination also involves ensuring that DER dispatch (via direct control or economic signal) doesn't create detrimental effects on the local distribution system, and will require schedule and dispatch coordination at the T-D interface between the TSO and DSO. At a minimum the DSO will likely be the best positioned entity to forecast net load in each local distribution area and net power flows across its T-D interface, based on visibility to all interconnected loads and DER in that area and the real-time status of all distribution facilities.

The need for **Energy Transaction Coordination** across the T-D interface is likely to increase with the growth of DER and related excess energy available for resale. This is due in part to the reality that most of the distributed generation and energy storage systems are not owned by customers, but by energy services firms that have the capability to market excess energy and capacity into the wholesale market. It is also very likely that energy transactions may occur within any given local distribution area between

[11] Micro-grids in this context means non-utility micro-grids involving privately owned electric networks on customers' premises. Examples include government facilities, business parks, corporate and college campuses.

[12] J. Taft and P. De Martini, Ultra Large-Scale Power System Control and Coordination Architecture, PNNL – Caltech, April 2014

[13] The question of regulatory jurisdiction will also need to be addressed; it is outside the scope of this paper but is identified below in the developmental roadmap section.

distributed generators, DER aggregators, municipal utilities, power marketers and energy retailers. At a minimum the physical aspects (not the financial aspects) of these transactions will need to be coordinated as part of the DSO's function of reliable distribution system operation. This does not mean that DSOs will operate balancing markets or an optimal resource dispatch function as done by the TSO at the wholesale level. Supply-demand balancing can remain the sole responsibility of the TSO. The DSO will, however, need to coordinate energy and capacity delivery schedules to ensure operational integrity of the distribution system.

It is important to clarify that the DSO functions described here do not require the DSO to be inserted into the economic transactions between parties involving DER and wholesale markets. Rather the core operational safety and reliability based DSO activities confine it to managing real and reactive power flows across the distribution system. These activities require tight integration of the people, processes and technology used to operate the distribution system. This is due to the highly dynamic nature of power flow on the distribution system and constantly changing local distribution area topology. As such, these functions should not be considered for separation into a third party independent of the DSO or TSO. To do so would add significant complexity requiring coordination across corporate boundaries to ensure the physical operation of the distribution system. This increases the operational and safety risk for field forces and the public, increases regulatory oversight and potential confusion on accountability, increases operational expense with no clear benefit to customers, and expands the cyber-physical attack surface for the integrated power system. If there are any concerns for conflicts of interest regarding the coordination of energy and capacity delivery schedules, these can be addressed by using standards of conduct (SOC) modeled after the successful Federal Energy Regulatory Commission's transmission operation SOC adhered to by utilities for nearly 20 years.

In restructured markets with separate ISO/RTO functions, the minimal DSO functions identified above will likely be performed by the existing UDC[14] for the reasons described. In this "Minimal DSO" model, the DSO ensures DER service deliveries to each T-D interface or P-node comply with distribution system safety, reliability and operational requirements. The DSO is also responsible to the TSO for providing situational awareness involving forecasting, real-time measurement and reconciliation of net load, dispatchable DER resource, real and reactive power flows from the distribution side of the T-D interface.

Figure 2 illustrates the integrated distributed electricity system concept as developed above. In the left-hand box dealing with distribution system operations, we first list the functions of the Minimal DSO and then identify several additional functions that might comprise an expanded DSO.

[14] There are instances where a P-node involves more than one UDC's distribution system. These cases will need to be considered in more detail.

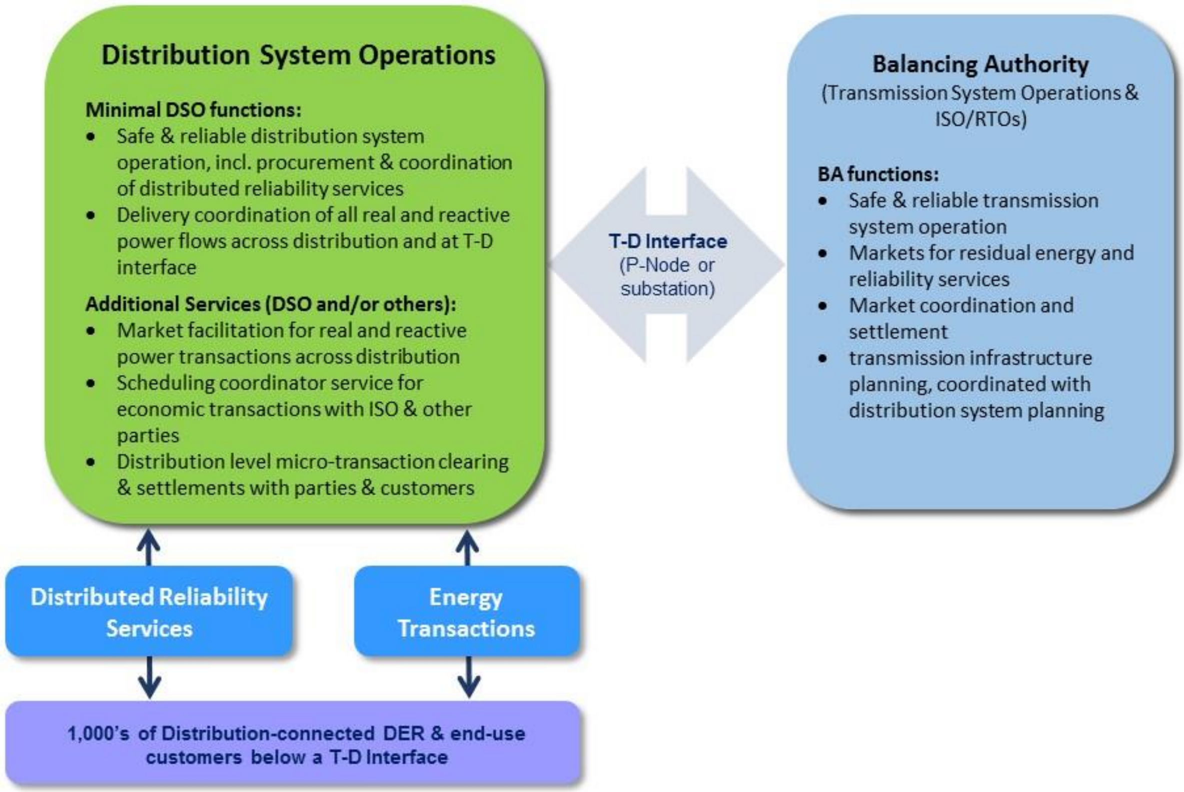

Figure 2: Integrated System Operations Framework

Beyond the Minimal DSO

Beyond these minimal functions, it is conceivable that a DSO could take on additional roles described below. The specifics and potential applicability of each additional role will be dependent on specific regional and local considerations. Also, there is a question of which industry participants might play these roles in the future. These ideas are offered to help frame the discussions beginning around the U.S. and internationally.

The **Dispatch Coordinator** is a possible model of a DSO with expanded functional responsibilities in addition to those performed by the Minimal DSO. In this model the DSO provides a single point of interface on the distribution side of a T-D interface for the purpose of operational dispatch coordination of all DER in the local distribution area that intend to participate in wholesale energy and ancillary services markets. This includes wholesale markets managed by the TSO for the P-node and broader regional markets as are increasingly available through arrangements such as the new energy imbalance market in the west and dynamic scheduling. In this role the DSO acts as the dispatch coordinator providing a consolidated offer to the TSO at each individual T-D interface.

Under this model the DSO consolidates and coordinates the energy transactions and ancillary or reliability services offered by individual DER, aggregators, services firms and customers into a single firm offer at a P-node. This means that the DSO would establish a secure clearing system to aggregate all participants' service offers and a transparent process for coordinating DER dispatch, including a pricing mechanism to reflect the dynamic constraints on the distribution system. in the ISO/RTO context this approach may offer substantial simplification for the TSO by allowing its market optimization to view the P-node essentially as a single resource offering to buy or sell energy and ancillary services, with the DSO on the other side of that P-node having full responsibility for managing responses to TSO dispatch instructions and accountability for any deviations from its scheduled interchange with the TSO.

The incorporation of energy storage into the distribution system may enable DSOs to offer new non-core market enabling services similar to those provided by natural gas distribution utilities. Such services may include "park and loan," where parties may park or store energy that cannot be delivered immediately to be scheduled for delivery at another time. Likewise, DSOs may sell or loan short-term real or reactive power as needed to make up for deficiencies in scheduled deliveries. The concept of "line pack" to increase the amount of energy that may be delivered in a short period may also be adapted to electric distribution systems with certain energy storage and demand management technology.

As the number of energy transactions rise across the distribution system and into the bulk power system, it may be desirable for DSOs to offer additional non-core micro-transaction clearing and settlement services. Transactions involved with distributed resources typically involve complex pricing structures and terms and very small individual dollar amounts per transaction. This is especially true when reliability services are unbundled. For California, this may involve a billion individual micro-transactions that require clearing and settlement at the scale envisioned in current public policy by 2025, driving the need for these services sooner than may be expected.

Recommended Guiding Principles

It is increasingly clear that the industry must begin to specify the operational functions of the Minimal DSO and design the optimal physical and information architecture to support those functions. The Minimal DSO can then provide the basic building blocks of the integrated distributed electricity system toward which the industry is evolving.

To that end, these guiding principles are offered:

1. The DSO will be responsible and accountable for providing safe, reliable (including resilience and power quality) and efficient distribution service for the local distribution area corresponding to an individual T-D interface substation.
2. The DSO will provide T-D Interface reliability coordination with the TSO for a local distribution area.
3. The DSO will provide physical coordination with the TSO for energy transaction across the T-D interface.
4. The DSO will procure distributed reliability services from qualified flexible DER to support distribution system operations. DSO will also provide necessary minimal services to DER to maintain reliable and safe operation. This specifically excludes any energy or renewable procurement to satisfy retail sales or renewable energy standards.
5. A regulated utility DSO will comply with standards of conduct to separate the natural monopoly functions entailed in operating the distribution system from potential conflicts related to energy sales, trading, generation production or other marketing efforts involving DER.
6. A DSO may operate multiple local distribution areas.

7. The functional requirements of the DSO should drive the physical and information architecture of the distribution system, not the other way around.
8. The DSO paradigm should enable public policy related to energy and environmental objectives including customer self-optimization, distributed energy resources, zero net energy and reduction of carbon and other emissions.
9. The DSO paradigm should enable the best new technologies to emerge and succeed, rather than picking winners through an administrative process.

A Development Roadmap for Integrated Electric System Operations

Designing the architecture, tools, systems and regulatory framework for the transition to the integrated electric system operations will involve a number of parallel tracks and sequential activities over the coming months and years. Taking the conceptual structure portrayed in Figure 1 as the high-level vision, and the operational design and specifications of the Minimal DSO as the basic building block, we suggest the following elements of a roadmap for continuing the effort.

1. <u>Operational Design and Research track</u>
    a. Develop the operational design and specifications of the Minimal DSO in greater detail, describing the necessary production activities to fulfill its core responsibility to provide safe, reliable distribution service for an individual local distribution area containing diverse DER and end-use customers. To simplify, initially treat the T-D interface as a single resource (such as a high-capacity, fast-response storage facility, for example); a later activity will add more realism to the T-D interface model.
        i. Conduct simulation modeling of the design. For example, use agent-based modeling for DER behavior and dynamic T-D power flow modeling to test and refine the operational design in a simulation environment.
        ii. Conduct simulation of real-time operational dynamics for the Minimal DSO to test limits of human interaction in real-time system operations. Assess the use of expert systems to augment real-time operational decision making.
        iii. Examine the implications of for the physical (electrical) distribution system infrastructure. Assess today's infrastructure for needed enhancements or redesign to support the new DSO functions most effectively.
        iv. Assess the operational requirements of the model and consider the design of situational awareness, decision support and control systems to support those requirements.
        v. Assess the role and potential for automated distributed control systems that minimize the need for human intervention as response times decrease.
        vi. Assess the information requirements of the model and consider the design of information and telecommunication infrastructure to support those requirements.
    b. Develop operational design for Dispatch Coordinator model to include a more detailed interface with the transmission system and wholesale market operated by the TSO. DSO functions would then include, among other things, coordination of purchases and sales of

energy and supply of ancillary services in the wholesale market. In this regard, consider the relative merits of having a single entity aggregate all bids from the local distribution area to the wholesale market versus allowing multiple entities to submit bids at the same T-D interface point or P-node.

i. Assess the design of Dispatch Coordinator from the perspective of the TSO, and consider how best to delineate the complementary roles and responsibilities of the TSO and the DSO.
ii. Consider operational aspects as well as physical system, controls and information infrastructure requirements.
iii. Consider information exchange and shared situational awareness requirements.
iv. Conduct simulation modeling to test and refine the design of this model.

c. Based on the preceding activities as well as lessons learned from any pilot projects (see track 2 below), develop an optimal or preferred design for the complementary roles and responsibilities of the DSO and TSO for the high-DER integrated distributed electricity system.

2. <u>Pilot Project track</u>
   a. In parallel to track 1, design and implement pilot projects to demonstrate the feasibility of a single entity performing the Minimal DSO functions for a single local distribution area below a single T-D interface. This may require some more limited preliminary pilots to demonstrate elements of the Minimal DSO functions prior to coordinating an entire local distribution area.
   b. As the designs for the Minimal DSO and Dispatch Coordinator models are developed, conduct pilot projects to demonstrate feasibility of design elements as appropriate.

3. <u>Policy, Business and Regulatory track</u>
   a. Develop the business model for the regulated monopoly Minimal DSO focused on the business of distribution service, considering both operational aspects and infrastructure activities such as planning and upgrading the distribution system and interconnecting new DER.
   b. Develop the business model for the Dispatch Coordinator design as a potential expansion of the Minimal DSO.
   c. Evaluate the Minimal DSO and Dispatch Coordinator designs developed for their effectiveness in supporting public policy energy and environmental mandates and goals.
   d. Consider the development and use of standards of conduct and related information and physical firewalls to separate the DSO function from other UDC functions including energy sales and generation production, similar to that with FERC’s SOC.
   e. Identify additional activities that may be performed by a DSO that is expanded beyond the Minimal DSO, distinguishing between activities that have natural monopoly characteristics and ones that are well suited to competitive provision. In particular, consider how to ensure a level playing field that will enable the best new technologies to succeed.

f. Identify the regulatory and jurisdictional aspects involved in implementing the Minimal DSO model, different variations of an expanded DSO, and different ways of delineating roles and responsibilities between the TSO and the DSO.

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