industrial internet CONSORTIUM

Applying the Industrial Internet Reference Architecture to a Smart Grid Testbed

An Industrial Internet Consortium Technical White Paper

Brett Murphy, Real Time Innovations (RTI)

Shi-Wan Lin, Thingswise, LLC

Brett Burger, National Instruments

IIC:WHT:IS2:V1.0:PB:20160718

Electric power systems across the world are under stress. Physical changes in the structure of the grid pose perhaps the greatest challenge. Renewable energy sources, distributed energy production, new energy storage systems and electric vehicles are rapidly shifting the power flows and control from a centralized power generation model to a widely distributed model with a strong focus on the edge of the grid. A new class of distributed monitoring and control schemes with intelligence across the grid, especially at the edge, is needed.

Market shifts also challenge the commercial aspects of the power grid. New techniques for reducing energy demands, especially during peak load situations, alleviate the need for new power generation. Variable pricing schemes and two-way power (from residential houses or commercial campuses back to the grid) promise new transactive markets for power. (For example, a homeowner can sell her extra solar power back to the utility or perhaps directly to another consumer on hot summer days).

The current power infrastructure is aging and in need of fundamental improvements. In addition, it is under rising threat from cyber-security incidents. Considering all these factors, there seems to be a perfect storm driving the need for fundamental changes in the power grid.

THE IIC MICROGRID TESTBED

It is in this context that National Instruments (NI), RTI and Cisco proposed the *Communications and Control Testbed for Microgrid Applications* as a testbed to the Industrial Internet Consortium (IIC) in 2015. Representing an emergent microcosm of the larger power grid, a microgrid is a strong solution for addressing some of the problems outlined above and presents an ideal Industrial Internet demonstration project for the power sector.

A microgrid is a section of the power grid with local power generation and loads that can be physically isolated (islanded) from the power grid. The local power generation is often from renewable energy sources with variable output level. For example, clouds can reduce the solar generation level very quickly. Therefore, the local generation level, power drawn from the power grid, local power storage and loads (where it is feasible), need to be monitored, coordinated and controlled rapidly to maintain stability in a microgrid. Local power storage[1] and quick response time in the control system of a microgrid are two important capabilities enabling the integration

[1] There are other examples of renewable energy integration without energy storage (e.g. grid-tied solar commercial installations).

of distributed renewable energy sources.[2] Moreover, the control capability provided by the microgrid at the edge of the power grid promises to increase the resilience of the overall power grid in the face of natural disasters or cyber-attacks. A microgrid is typically deployed for a large campus (for example, college and corporate campuses, large hospitals, large factory sites and residential communities) and operated by the owners of these properties, commercial operators or utilities.

Approved in March 2015, the testbed team began developing Phase 1 of the testbed project with a proof-of-concept demonstration integrating CompactRIO intelligent nodes from NI, DDS-based data communications from RTI and grid-connected routers from Cisco. The first public demonstration of the testbed was at the IIC's Niskayuna NY public meeting the following July. Then in September 2015, the team demonstrated a more extensive proof-of-concept at the IoT Solutions World Congress in Barcelona, Spain. Phase 1 completes with a more permanent demonstration installation at NI headquarters in Austin TX. The next phases will include deployment of the communications and control framework in the field.

The communication and control framework under development is consistent with the IIC's *Industrial Internet Reference Architecture* (IIRA). Basic communication and control capabilities are instantiated through software and hardware products from the testbed team companies. New capabilities like mobile application platform integration and cloud-based analytics from new team members Waygum and IBM prove the extensibility and interoperability of the Industrial Internet of Things (IIoT) systems and the benefit of applying IIoT's concepts and models to streamline the creation of microgrids. First integrated early last year, the framework was instantiated before the first IIRA draft was published. As an exercise to test the relevance and value of the IIRA, the microgrid testbed team and members of the IIC Architecture Task Group worked together to apply the IIRA to the microgrid testbed architecture, the result of which, including some of what we learned, is reported in this white paper.

Applying the IIRA

The key requirement for a microgrid is to ensure stable electricity supply to meet local energy demand using local generation under dynamic demand and supply conditions and when the power grid is under stress due to unfavorable natural conditions or cyber-attacks. The local generation is often renewable, which in turn provides the motivating commercial value. To meet this requirement, a microgrid needs to provide a key capability to dynamically monitor, coordinate and control local power generation, storage and consumption, as well as its operating state relative to the power grid so as to maintain local stability. To achieve a higher level of operational efficiency, the microgrid shall continuously sense and forecast local power generation, storage and load conditions. It shall then dynamically create and execute optimized

[2] Advanced metering is another enabling technology that makes microgrid commercially viable.

operating plans based on local operational information, and technical and commercial information about the power grid to which it is connected. These operation plans include adjusting the power generation, storage and loads profiles and entering and leaving islanded mode based on the availability of generation resources, storage capacity, consumption demands, power grid condition and pricing, and contractual obligations.

Given the diverse sets of power equipment and loads within a microgrid across a large campus, and the dynamic nature of its local operation and of the conditions of the power grid, a microgrid is necessarily a complex system that must be managed with real-time distributed control. As the renewable generation level gains and wanes and the demand varies, the system decides if it is to increase storage level in power storage equipment or to supply stored energy to compensate the shortfalls in the generation and to adjust loads to moderate demand under stress. This complex system involves sensing and collecting large amount of data, analyzing these data to obtain operational intelligence and creating and executing operating plans based on the intelligence to achieve operational objectives 24x7. Systems with this type of complexity and dynamism are just what the IIRA intends to facilitate in its system conceptualization and architecture.

With a stress on commonality, the IIRA identifies important architectural issues in IIoT deployments across industrial sectors and explores broadly applicable resolutions to these issues. It aims to establish conceptual mindshare and a common architecture framework that can be used as a higher-level starting- point for conceptualizing and designing IIoT systems and for guiding the development of interoperable architecture building blocks and assembling them into complete systems.

The IIRA provides a framework to examine the concerns of an IIoT system ranging from conceptualization, to design and implementation. It classifies these concerns into four *viewpoints*: the business, usage, functional and implementation, as shown in Figure 1. The concerns in each viewpoint can then be elaborated systematically. The expression and resolution of the concerns in these viewpoints inform and enhance each other, generally through an iterative process.

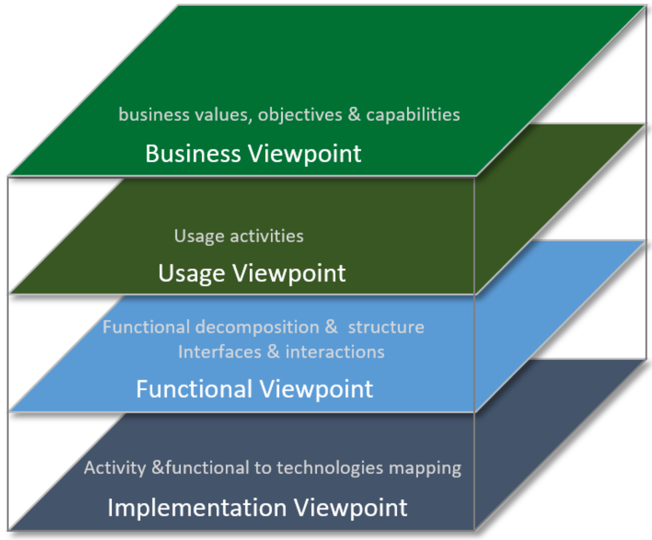

Figure 1 The Viewpoints in The Industrial Internet Reference Architecture

The Business Viewpoint

Before diving into the details around analyzing the concerns in the business viewpoint, the IIRA suggests identifying the stakeholders of the IIoT system in question so that the concerns can be better understood and resolved. For the microgrid testbed, we identify the following *key stakeholders* and their key concerns for the conceptualization, building, operating and use of a real-world microgrid system:

The *owner/operator* of the microgrid is the key stakeholder in driving the conceptualization, construction and operation of the microgrid. Their key concerns include how to increase the energy resilience, cost-effectiveness and "green-ness" of their power consumption, and how to create and deploy a quality implementation of a microgrid system that operates reliably, is easy to maintain and is capable of delivering the expected business value. Examples of owner/operators include large corporations with large campuses, factory owners, large hospitals, university campuses or system integrators that offer "microgrid-as-a-service" to these owners.

System integrators are organizations contracted by the owner/operator to design and build the microgrid. The System Integrator (SI)'s key concerns are how to run a high-quality system development and integration program to achieve customer satisfaction and their own profitability. Note that the SI can also be an operator under contract to a customer long-term.

Utility operators are the power grid operators who own and operate the power grid to which the microgrid will be connected. Their foremost concern is to ensure that the microgrids' interactions with the power grid do not destabilize the power grid as they import power from or export power to the power grid and when they enter or leave their island mode of operation. The utility operator is also concerned with how to ensure well-behaved load profiles from the operational microgrid especially with renewable energy source variability and to interface with the microgrid for advanced use cases like *demand response*[3]. Finally, the utility operators also wish that their business models are not negatively affected by the microgrid.

The *customers* are the users of the electricity, either internal or external, or both. Their main concerns are how to have stable, always-available electricity at economical prices. Increasingly, customers prefer green generation sources.

The IIRA business viewpoint provides simple guidance on how to address the business related concerns for initiating an IIoT system. These address some fundamental business-related questions such as what it is we want to build, why we want to build it and whether the value from what we build will justify the investment. With a high-level understanding of these and related questions, the key stakeholders can guide the process of conceptualizing, building and operating the system. The following are the results of our attempt to apply the thought process from the IIRA business viewpoint to the microgrid testbed from the owner/operator perspective, as they are the key stakeholder likely to be the initiator and driver of a microgrid. It starts by identifying the vision of what the microgrid would bring about; it then derives some tangible business value propositions from and in support of the vision; it further derives concrete and measurable key objectives in realizing the business values; and finally it arrives at a set of fundamental system capabilities required for achieving the key objectives.

Vision: To achieve a high level of self-sufficiency and self-control in electricity supply that is reliable, economical and environmentally friendly.

Values:

- Increase efficiency, minimize consumption, reduce environmental impact and improve reliability of supply;
- Reduce cost or even generate revenue by optimizing generation, storage and consumption based on the power grid pricing schedule;
- Contribute to the global resilience of the power grid; and
- Help meet government regulations on renewable energy penetration.

Key Objectives, for example[4]:

- Self-supply; 75% electricity with 45% renewable generation;
- Reduce cost by 15%;

[3] Demand Response involves energy customers reducing their power consumption on request from a utility, as opposed to increasing power generation within the grid.

[4] The numbers are speculative for now. The proper numerical numbers in the objectives are part of what the testbed set out to explore to provide some guidance to the real-world implementations and they will be detailed in a testbed report with actual results.

- Reduce outage rate to 0.0001%;
- Reduce greenhouse emissions by 65%; and
- Enhance security of local electricity supply, meeting or exceeding regulatory requirements or best-of-breed industrial standards.

Fundamental Capabilities

- Predicting renewable energy resource availability and near-term local generation levels in advance to allow enough time for the utility to adjust power generation;
- Analyzing supply, consumption, price, cost, generation resource availability and asset conditions in real-time to create:
  - optimal demand response plan under constraints;
  - optimal generation plan balancing local generation level, drawing from/feeding to the grid and drawing from/storing in local storage and
- Operating independent of the power grid (island mode)—dynamic switching between *connected*, *transitioning* and *island* modes based on physical data about the grid.

This exercise is an iterative process requiring deliberation, research and careful analysis by key stakeholders with strong business and technology backgrounds. It should arrive at conclusions based on the vision, available evidence in support of the business value in light of the required investment, the feasibility, risks and constraints; on what system to build, how to build and operate it; and in the end whether to build it at all. The results of the analyses will guide the construction and the operation of the system throughout the lifecycle if it is built. The analyses also guide the development of the subsequent viewpoints, system requirements and possibly metrics for measuring success at each stage of the lifecycle.

Usage Viewpoint

The IIRA usage viewpoint describes how the system is to be used to deliver the fundamental system capabilities identified in the business viewpoint. It identifies conceptual key system and human actors and describes how they interact with each other and the environment in a number of key usage scenarios. The analysis in this viewpoint further enhances the understanding of the system to be built and provides feedback to the business viewpoint by validating or revising its premises.

For the microgrid testbed, we identify a number of major conceptual system actors (components) and their interaction flows in four different usage scenarios, as shown in the figures below. These system actors are:

Generation: The class of power generation assets of various kinds, ranging from conventional fossil fuel to renewable generation that may have highly variable output.

Storage: The class of power storage assets such as batteries.

Loads: The class of power consuming assets, from lighting, heating and cooling, and all other power consuming equipment and machines. Some of these assets may be considered operationally critical, the interruption of which may cause severe economic consequences or have safety implications.

Point of Common Coupling (PCC): A power-coupling switch between the microgrid power system and the power grid that controls the connection of the microgrid to the power grid.

Controller: A microgrid main controller that provides supervisory control commands to the other components, and communicates and coordinates with the power grid. If local generation fades and the system is not connected to the grid, for example, the controller will command the battery backup to provide power.

Intelligent director: The class of computational assets performing data collection and analytics to provide intelligence to operate the power (generation, storage and consumption) assets.

We analyze four major usage scenarios using these abstract system actors and their associated interaction flows as depicted in the following diagrams. They are a first step in analyzing the system from a usage point of view. These scenarios are not complete, but serve as examples or templates for other scenarios. Subsequent analysis must follow to round out the next level of detail, such as breaking down the class of assets into its concrete constituent instances, thus making it possible to analyze their variations.

In all scenarios, we assume the system is continuously collecting operational data from the assets and coordinating the operations of these assets. We also assume the system is integrated and coordinating with other information systems, including business systems, to obtain all required inputs ranging from operation plan (for example, power demands), business (for example, costs of generation and pricing schedule) and environment (for example, weather forecast) information.

Peak Hour Adjustment

In this usage scenario, the system arrives at a peak-energy-usage time window in which the power demand is high across both the microgrid and the power grid. Consequently, the price of power from the power grid is high as well. It is desirable to generate as much power within the microgrid as possible at a favorable cost, reduce load where feasible, use stored energy intelligently to balance the demand, supply, cost and emergency reserve and provide surplus electricity to the power grid to reduce its stress and to gain financially by doing so.

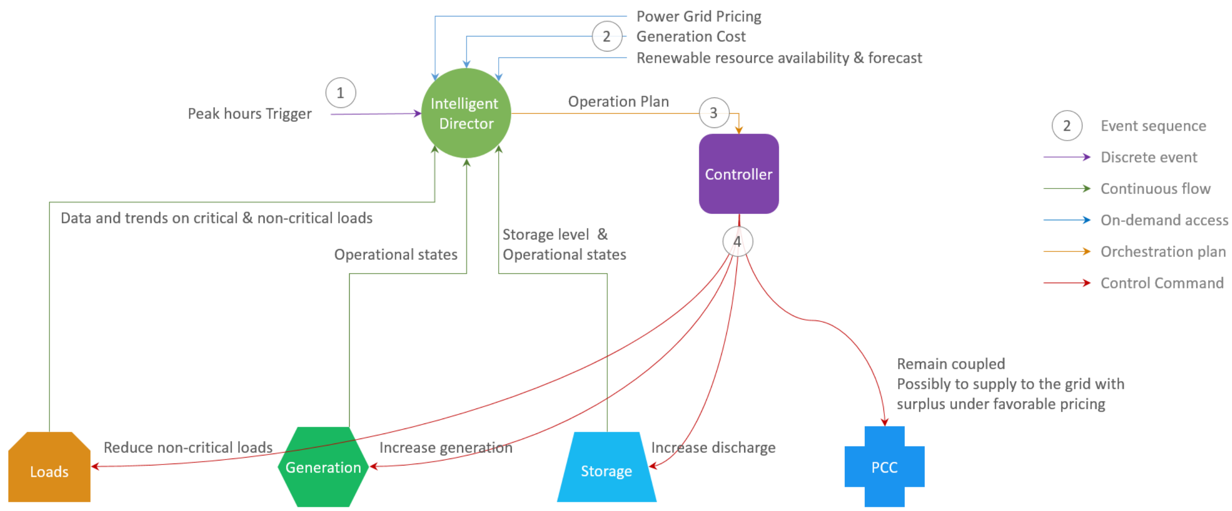

Figure 2 The peak hour adjustment usage scenario

The sequence of conceptual interactions of the system actors is as follow:

1. The system receives a peak-energy alert from the main grid operator.
2. The intelligent director gathers an update on the necessary information from other information systems on power grid pricing, the generation costs of its generation fleet and the forecast of availability of the renewable resource.
3. The intelligent director creates an operation plan for the next period optimized based on the information obtained in step 2, the current operational states of the generation and storage assets, and the current and forecast of loads. It then dispatches the operation plan to the controller.
4. The controller validates the operation plan and dispatches the necessary coordination commands to the assets, for example, to increase generation of certain types, to increase discharge of energy storage, to reduce unessential loads and possibly provide surplus to the power grid.
5. The intelligent director continuously monitors the operational state of the assets and power grid conditions and makes necessary adjustments to the operation plan to accommodate new changes and exceptions (not shown in the figure).
6. The intelligent director may also provide demand or supply forecast information to the power grid so that the power grid can balance its operations better (not shown in the figure).

Off-Peak Hours Adjustment

In this usage scenario, energy is being generated by the renewable sources in the microgrid and energy distribution can be optimized based on multiple factors:

- the current energy load demand in the system,
- the current price of energy that the local grid operator (a utility) will pay for energy provided back to the main grid,

- the current price of energy from the grid,
- the current charge state of the local energy storage devices and whether charging is needed, and
- The time of day and projection of energy needs in the microgrid for the coming hours

Using these factors, the microgrid optimizes how energy should be produced and used.

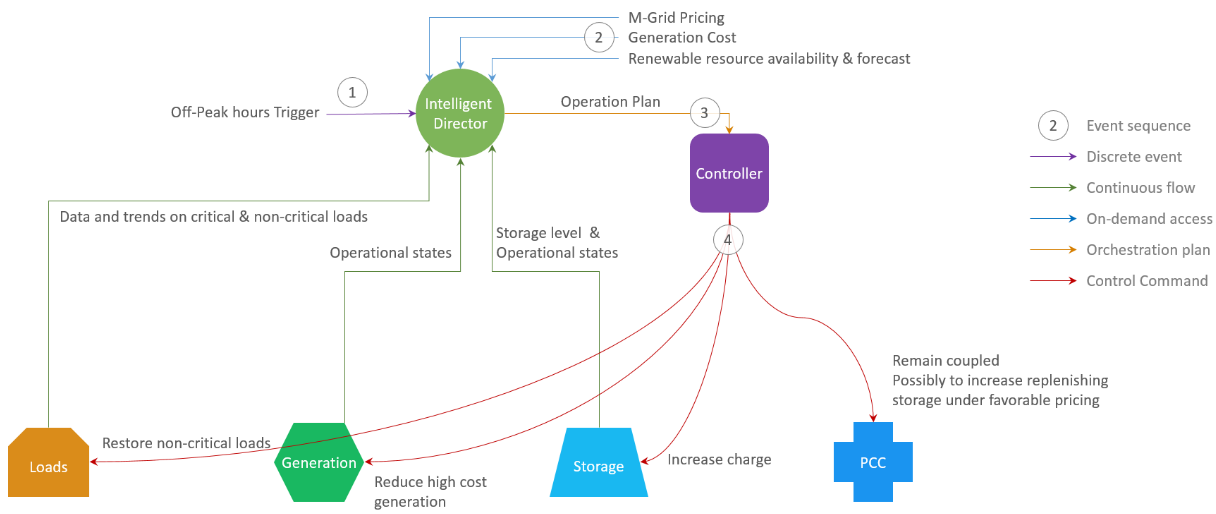

Figure 3 The off-peak hours adjustment usage scenario

The sequence of conceptual interactions of the system actors is as follow:

1. The system determines that it is an off-peak hour system state
2. The intelligent director gathers an update on the necessary data from other information systems on power grid pricing, the generation costs of its local energy sources, the forecast of availability of the renewable resource and other values.
3. The intelligent director creates an operation plan for the near future that is optimized based on the information obtained in step 2. It then dispatches the operation plan to the controller.
4. The controller dispatches the necessary coordination commands to the assets.
5. The intelligent director continuously monitors the operational state of the assets and power grid conditions and makes necessary adjustments to the operation plan to accommodate new changes and exceptions (not shown in the figure).
6. The intelligent director may also provide demand or supply forecast information to the power grid so that the power grid can better balance its operations (not shown in the figure).

Renewable Resource Unavailable

In this scenario, the local, renewable power generation begins to lose power, perhaps as clouds reduce a solar array's output or the wind dies down. In this situation, rather than immediately drawing from the power grid, local backup energy storage should be used and near-term power demand reductions may be sought. In addition, a request for additional power can be made to the power grid depending on the near-term power-generation forecast (which usually depends on local weather forecasts). As a result, the system provides a better-behaved and smoother power-load curve to the power grid allowing the main grid operator to spool up backup power sources more efficiently and to reduce peak load demand.

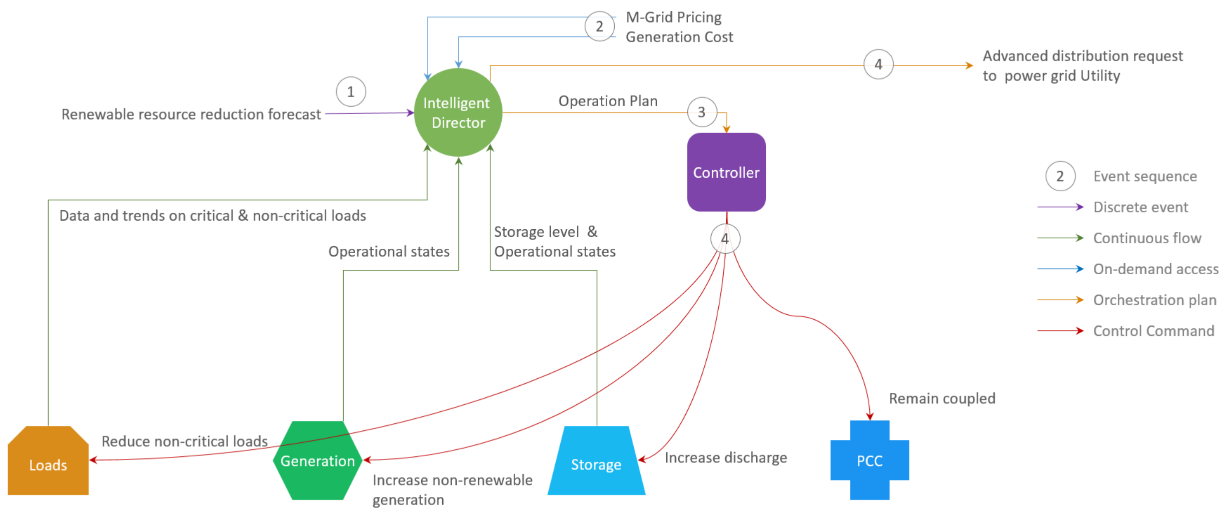

Figure 4 The renewable resource unavailable usage scenario

The sequence of conceptual interactions of the system actors is as follow:

1. The system detects an immediate or pending renewable energy reduction alert. This could come from the controller monitoring the local renewable resources or an external energy forecast service.
2. The intelligent director gathers an update on the necessary information from other information systems on the state of the local energy storage systems, the demand load forecast and availability of demand response resources (what loads can be rapidly shed) and the forecast availability of the renewable resources.
3. The intelligent director creates an operation plan for the next period that is optimized based on the information obtained in step 2. It then dispatches the operation plan to the controller.
4. The controller validates the operation plan and dispatches the necessary coordination commands to the assets, for example, to increase generation of certain types, to increase discharge of power storage and to reduce unessential loads. In addition, the intelligent director dispatches an updated power distribution request to the main grid operator for the near-term period.
5. The intelligent director continuously monitors the operational state of the assets and power grid conditions and makes necessary adjustments to the operation plan to accommodate new changes and exceptions (not shown in the figure).

Power Grid Outage and Recovery

This usage scenario covers the situation where the local microgrid is islanded due to a main grid outage. The microgrid must immediately respond to provide power to critical systems in the local service area. The current state of power generation, the state of energy storage systems and demand levels will dictate what the response would be. When the main grid is restored, local power sources must be synchronized to the grid before the microgrid can be reconnected to the main grid.

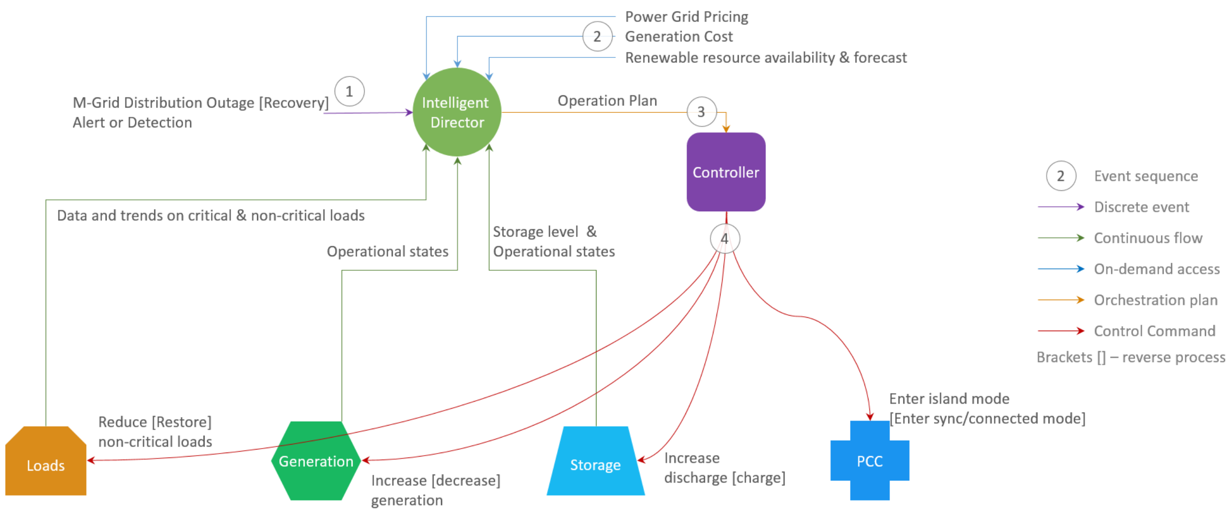

Figure 5 The power grid outage and recovery usage scenario

The sequence of conceptual interactions of the system actors is as follows. First for outage:

1. The system detects the loss of the power grid. This alert is generated by the PCC when it triggers based on the grid failure. (Alternatively, the power grid operator may give advanced alert of such outage to the microgrid so that the response may be triggered by the intelligent director.)
2. The intelligent director gathers the necessary information from other information systems on the state of the local energy storage systems, the demand load forecast and availability of demand-response resources (what loads can be rapidly shed) and the forecast availability of the renewable resources.
3. The intelligent director creates an operation plan for the next period that is optimized based on the information obtained in step 2. It then dispatches the operation plan to the controller.
4. The controller validates the operation plan and dispatches the necessary coordination commands to the assets, for example, to increase generation of certain types, to increase discharge of power storage and to reduce unessential loads.
5. The intelligent director continuously monitors the operational state of the assets and power grid conditions and makes necessary adjustments to the operation plan to accommodate new changes and exceptions (not shown in the figure).

Now for recovery:

1. While in the outage mode, the system detects the recovery of the power grid via an alert from the PCC.
2. The intelligent director gathers updated system state information to update the operational plan if needed.
3. The intelligent director creates an operation plan for the next period that is optimized based on the information obtained in step 2. It directs the controller to begin the recovery sequence and dispatches the operation plan to the controller.
4. The controller dispatches the necessary coordination commands to the assets. Specifically, it uses the main grid phase information collected by the PPC to direct the necessary phase shifts for the local power source assets.
5. The controller monitors the phase information on the microgrid side of the PCC and the main grid side of the PCC. When sufficiently synchronized in phase, the controller directs the PCC to reconnect to the main grid (not shown in the figure).

Functional Viewpoint

After gaining sufficient understanding of how the system is to be used, the IIRA functional viewpoint offers a way to examine the system from a functional perspective. It focuses on the functions the system must provide to support the intended usages, the interactions and activities of its actors. In the analysis, it decomposes the system functionally, identifies its key functional building blocks, the relations and interactions between them and the interfaces through which they interact. Each of the functional building blocks can then be further decomposed, yielding more detailed and concrete descriptions of the system at each iteration until the functional design of the system is fully realized. The IIRA provides a concrete functional model consisting of five distinct functional domains that are intended to be widely applicable in IIoT systems.

The five functional domains, as summarized in Figure 6, are briefly outlined as follows:

Control (asset) domain: a collection of functions performed by the industrial assets or control systems in executing closed-loop control[5]. While generally performing their functions independently and in some cases autonomously to maintain their continuing operation, the assets may interact with other assets in proximity and be coordinated by higher-level systems in other functional domains.

Operations domain: a collection of functions for assets and control systems management and maintenance to ensure their continuing operations.

Information domain: a collection of functions for collecting, transforming, analyzing data to acquire high-level intelligence of the entire system.

---

[5] The continuous process of reading sensor data, applying analytics, rules and logic on the data and exercise control over the assets through actuation to achieve the desired physical effect.

Application domain: a collection of functions for applying use-case-specific logic, rules and models based on the information obtained from the information domain to achieve system-wide optimization of operations.

Business domain: a collection of functions for integrating information across business systems and applications to achieve business objectives.

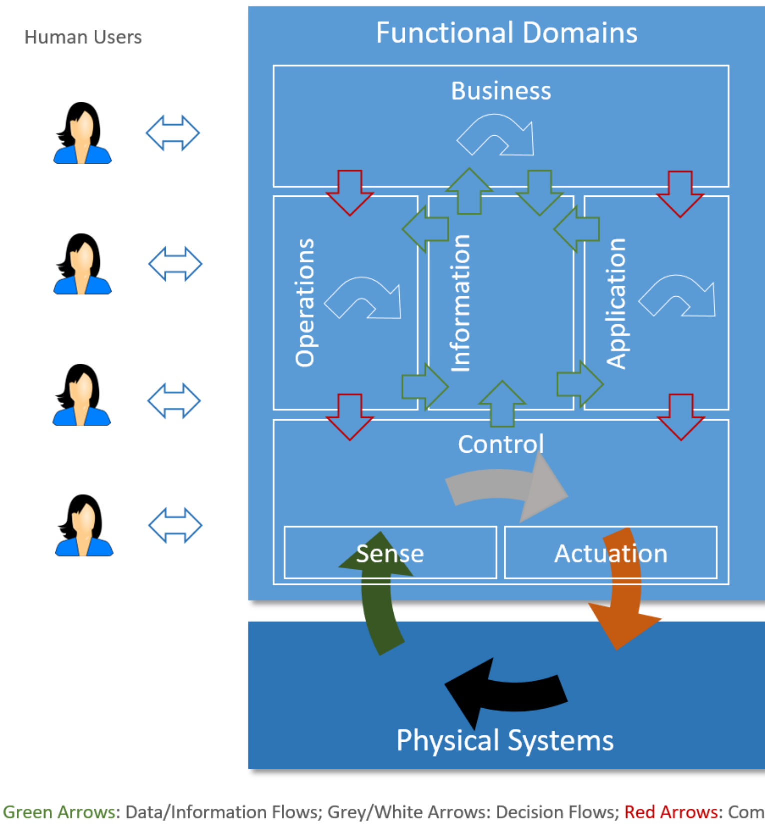

Figure 6 The functional domains in the Industrial Internet Reference Architecture

In the case of the microgrid testbed, this set of functional domains seems to apply rather well as shown in the following diagram. It highlights the key functional elements that a microgrid system needs to implement to realize its system capabilities fully. It also exposes the interfaces the functional elements must support and the flows of data, information and commands across these interfaces, as depicted in Figure 7.

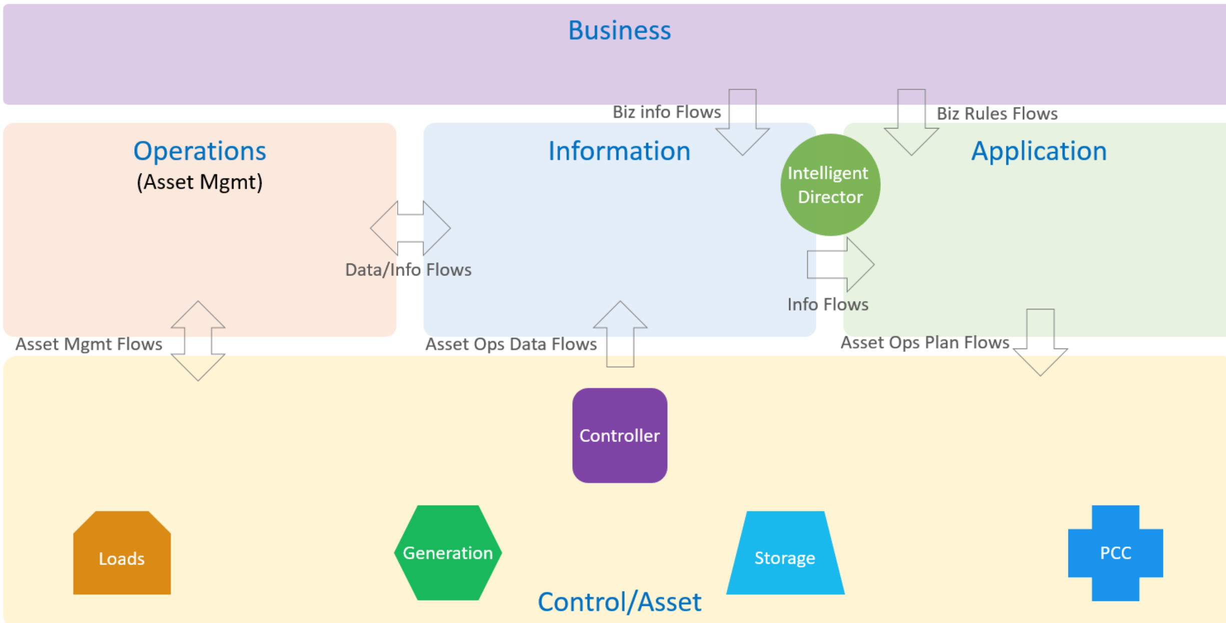

Figure 7 The functional viewpoint

Control (asset) domain: The core functions performed by the assets of the power generation, storage, loads and other physical elements falls into this functional domain. These assets implements functionality to enable their remote management, operational state data sharing and acceptance of coordinating commands from higher-level elements.

Operations Domain: To maintain continuing operations of the power assets, remote management capability is needed for remote health monitoring, configuration and update, diagnosis and preventive maintenance. Currently, the microgrid testbed does not address this domain, but may in the future.

Information Domain: This is a set of core functions in the microgrid that gather all the necessary data and information from the assets, business and other information systems and perform analytics on them to acquire intelligence to best optimize operations.

Application Domain: This is a set of functions that apply business rules and logics based on the intelligence supplied by the information domain and guided by the business objectives to create optimal operation plans and dispatch them to the controllers in the control domain.

Business Domain: This is a set of business functions such as work planning, customer relation management (CRM), enterprise resource planning (ERP), manufacturing execution system (MES), etc. that the microgrid may need to integrate and interact with to achieve fully automated or autonomous operations. The microgrid testbed does not address this domain now, but may do so in the future.

Note that the intelligent director in the usage viewpoint is supported by functional components in both the information and application domains. Functions in the information domain provide the intelligence for the assets' operational states and other aspects of the system and the environment. Functions in the application domain act on the intelligence and apply usage-specific rules to ensure the desired operational outcomes. This partition of functions allows the possibility of leveraging any existing common data and analytics platforms to perform the needed analytics without starting from scratch. This in turn allows the team to focus on the domain-specific logic in the application domain.

Implementation Viewpoint

With general understanding of the key functional blocks, the implementation viewpoint examines:

- how these functional blocks are organized and distributed as system components in a network topology based on the deployment requirements,
- how they interact with each other to support the activities identified in the usage viewpoint and
- what technologies to use to implement for the components.

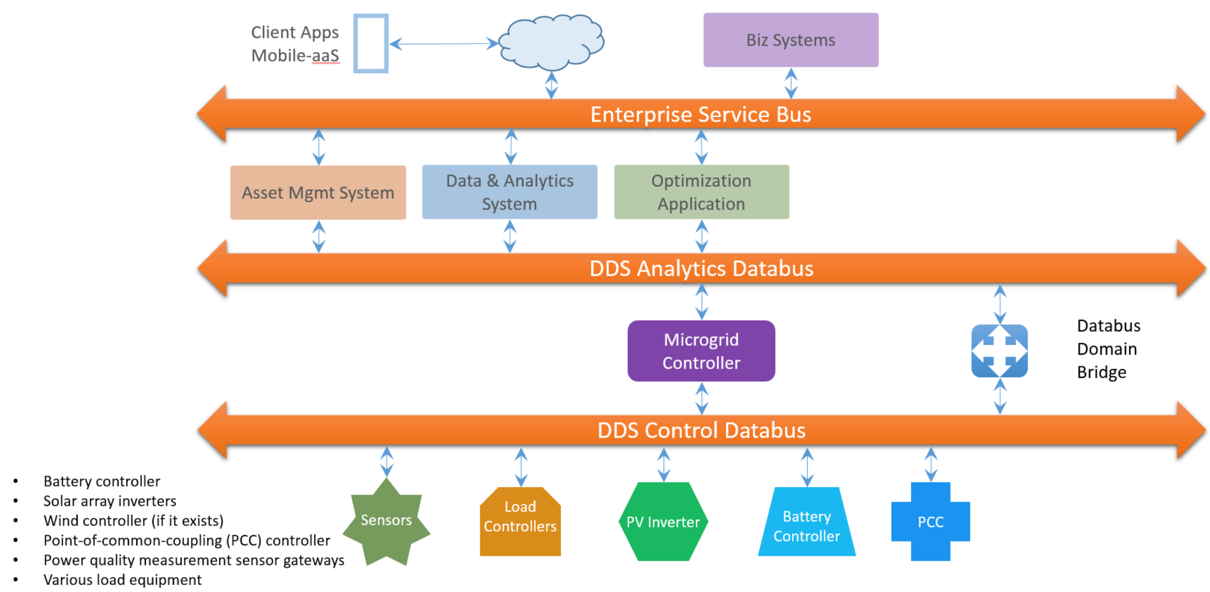

Figure 8 The implementation viewpoint[6]

Projecting the microgrid testbed deployment at a medium-sized facility microgrid, we have used the layered databus[7] architecture implementation pattern (a specific implementation of the

---

[6] The PV Inverter is illustrative for the cases of photovoltaic energy conversion in solar power generation; other types of converters will be used for other types of generation.

[7] A databus is a data-centric information sharing technology that implements a virtual "global data space". This is fundamentally different from the more-traditional messaging systems. With a message-centric approach, developers write applications that send messages between participants. With a data-centric approach, developers write applications that read and update entries in a global data space.

IIRA's 3-tier architecture pattern), as depicted in Figure 8. In this architecture pattern, the edge databus layer consists of the assets and their controllers at the bottom of the diagram above. The analytics databus layer maps to the 3-tier pattern's platform tier and supports the asset management system, data and analytics system and the microgrid domain optimization application. The enterprise tier at the top of the diagram supports integration with business systems for the deployment site, as well as mobile applications integration through a mobile-as-a-service platform. Based on the low latency, reliability and scalability requirements and the many-to-many connectivity pattern at the control layer, we plan to implement a DDS-based databus supporting the OpenFMB smart grid data model solution[8]. The analytics databus layer supports communication between various data storage, analytics and optimization applications and services. The data communications is highly dynamic depending on the system configuration and use scenario (islanded mode requires very different optimization algorithms than peak-energy mode), so again we plan to use DDS as the databus solution. However this is a logical databus representation as some of the applications reside on near-edge servers (fog compute nodes) while others reside in remote "cloud" servers. Partitioning the databus into two segments also provides additional security isolation to the control databus involved in actuation commands.

Key System Characteristics

The IIRA has a strong emphasis on key system characteristics such as safety, security and privacy, resilience, and performance and scalability as emerging system behaviors from its constituent components and their interactions in an IIoT system. These key system characteristics must be identified, analyzed and understood early in the system conception and design process; they are difficult to address at a later stage.

A microgrid testbed must consider a number of important key system characteristics:

Safety: Because a microgrid deals with electricity generation, storage and consumption, existing safety requirements and regulations must be followed. Moreover, because a microgrid manages the traditional generation and distribution of power and the consumption of electricity, it may have additional safety requirements such as preventing incorrectly shutting down the electricity supply to essential services.

Security and privacy: As in the case for other infrastructure services, security requirements for a microgrid need to address how to protect the system from intrusion, interference of its operation or worse, its destruction. There are also requirements for protection of its data including those regarding its business operations and for its customers' business concerns. These aspects will be analyzed in depth in a separate process.

[8] OpenFMB project page: http://www.sgip.org/openfmb/

Reliability and resilience: A basic requirement for a microgrid is the constant availability of power in spite of system faults, unfavorable environmental conditions, disruption of power supply from the power grid, malicious attacks and other factors such as human operational errors. How to achieve the required reliability and resiliency requires study as a next step in the system design process. One design principle stands out, as in many other industrial systems, the continuing operations of the assets should not depend on the availability of the IIoT network or the operational state of peer systems. There should be a default operational mode in which the individual assets maintain their operations to provide service at or above a minimum level even under unfavorable or adversarial conditions. When unfavorable or adversarial conditions are removed, the assets and system as a whole should attempt to recover from the conditions and restore to their normal operational states. Nevertheless, how to design a system with reliable components, a reliable network and with a certain level of redundancy for critical elements are important considerations. For example, a key advantage of the DDS databus is its reliable communication in handling single node failures and in its ability to provide reliable data delivery, for example, when a failed node recovers.

Performance and scalability: The performance and scalability factors that may be considered in a microgrid include:

- *Latency*: What are the network latency requirements between the assets and the controllers? What communication latency between the controllers and the assets are permissible in order to avoid unsynchronized or contradictory behavior in the system?
- *Data volume and rates*: What are the data collection volume and rates that are required for performing adequate analytics?
- *Adjustment cycle*: How often does the system need to adjust the operational states of the assets? How quickly does the system need to respond to unfavorable or adversarial conditions in order to avoid or minimize any undesirable effects on the customers and their equipment?

In addressing this set of issues, it is useful to understand the size of the system in terms of the number of assets of each type to be managed and controlled.

WHAT WE LEARNED

- The testbed team was focused on integrating core capabilities and demonstrating basic use cases. This exercise of applying the IIRA to the testbed enabled us to step back and approach the system development from the perspective of the stakeholders and their business needs. Explicitly capturing those factors broadened the applicability of the communications and control framework in the testbed. For example, it clarified that the owner/operator, system integrator and utility could and likely will be separate organizations. Instead of focusing solely on the system integrator, we had to include the requirements for these other stakeholders.

- The IIRA provides a systematic way to address various business and technical concerns with the framework of viewpoints. It also supports an iterative development process and collaboration between ideas about the system among the viewpoints. For example, the usage viewpoint helped the team think through and visualize the usage scenarios, which in turn helped the team detail the functional and implementation viewpoints.
- Mapping the elements of the microgrid to the functional viewpoint led us to clarify the various domains of that viewpoint. For example, it clarified where to capture the high-level analytics function versus the functions applying domain-specific rules. This separation also offers the opportunity for the testbed to look for common analytics platforms to avoid implementing the complex functions from scratch. It also identified the need for asset management functions that had not been emphasized.
- The multi-tier architecture patterns in the IIRA implementation viewpoint offer guidance in analyzing how the functional components can be distributed across a network topology that is appropriate to the testbed.
- In analyzing the key system characteristics as a required step of the IIRA, it simplifies the task by laying out important categories such as resilience, safety and security. It also reminded the team to address the needs of all the Stakeholders identified earlier.

In summary, the IIRA with its multi-viewpoint framework and its emphasis on key system characteristics helped elevate the system analysis of the microgrid. It supports an iterative and collaborative method to analyze the system. It helped identify some issues that were not previously considered and to clarify some others that were previously unclear. As a reference architecture, the IIRA is a good starting point for conceptualizing and designing the system by setting a foundation for doing so. However, many iterations of analysis, each with increasing depth, based on this foundation are required to detail the architecture and design before the system can be fully implemented.

About the Industrial Internet Consortium

The Industrial Internet Consortium® (IIC™) is a global, member supported, organization that promotes the accelerated growth of the Industrial Internet of Things by coordinating ecosystem initiatives to securely connect, control and integrate assets and systems of assets with people, processes and data using common architectures, interoperability and open standards to deliver transformational business and societal outcomes across industries and public infrastructure. The Industrial Internet Consortium is managed by the Object Management Group (OMG). For more information, visit www.iiconsortium.org.