Synchronized and Business-Ready Microgrid

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Since we discovered electricity, we have been fascinated by it. Easy transformation from and into other forms of energy—such as chemical, mechanical, optical and thermal—has played an important part in improving living conditions and advancing society. Through the brilliance of Benjamin Franklin, Michael Faraday, Thomas Edison, Joseph Swan, Nikola Tesla, James Watt, André Ampere, George Ohm and millions of engineers, electricity is now such a ubiquitous part of our modern life that we take it for granted.

Historically, the electric grid was designed for centralized generation and one-way transmission and distribution, but the emergence of new generation and storage technologies, such as solar, wind and battery, is challenging that. These technologies are installed on the periphery and are capable of feeding significant power back into the main grid. However, the existing grid relies on alternating current (AC) and power generation sources with mechanical rotation. These classic power generators rely on the physics of electrically connected motors to automatically keep the phase and frequency of the AC signal synchronized. On the other hand, renewable energy sources such as solar and batteries are usually direct current (DC) and so require conversion into AC at the exact phase and frequency as the main grid. These differences pose many operational difficulties for the foundational design principles and technical assumptions that were used for the construction of the power grid.

This paper outlines an approach to address operational challenges faced by existing electric grids by integrating communications and control technology directly to the grid. Advances in embedded systems, analytics, machine learning and time-sensitive networking allow tightened integration, thereby digitalizing the grid and solving technical problems that were hitherto considered impossible to solve.

The Challenge

Interest in solar and wind power generation continues to increase today because of:

Pollution: Traditional fossil-fuel-based generators cause greenhouse emissions, and people are wary of nuclear power after the Fukushima reactor disaster.

Disaster prevention: Renewable energy resources at the edge of the power grid diversify energy generation and make grids more resilient.

Cost savings: After an up-front investment in solar or wind installation, businesses and homeowners can reduce their energy bills substantially over time.

However, existing electric power transmission and distribution systems were not designed to manage large numbers of distributed energy resources (DERs) that produce variable power like solar and wind. A solar array can lose and regain power in milliseconds with a fast-moving cloud, or the wind can suddenly drop, so an alternate source has to be available and ready to pick up the load immediately. It can take up to fifteen minutes to spin up (or down) a centralized generation plant as necessary, and even longer for large-scale thermal plants. Since the supply has to match demand for proper electrical operation, the voltage or frequency on the grid can drop and lead to grid failure.

To avoid this, utilities keep excess, reserve power generation ("spinning reserve") to smooth the fluctuations. The more severe the fluctuations, the more excess reserve power generation the utility has to have ready as backup. It needs to be reliable and responsive which requires traditional rotating power generators. Since DER generation can vary significantly, utilities have to keep significant reserve, which burns fossil fuels and wears out bearings. It can also impose unintended cooling costs for unused power.

Microgrids are a way to address some of these issues. Microgrids are grids that cover a small geographic region with some local control capability over a combination of intermittent energy sources such as solar and wind, and energy storage systems such as batteries. They can therefore respond rapidly and locally to power generation fluctuations and smooth the demand on the main grid. This can provide an additional 15 to 30 minutes of time for the utility to ramp up an additional generator and reduce the need for spinning reserves (see Figure 1).

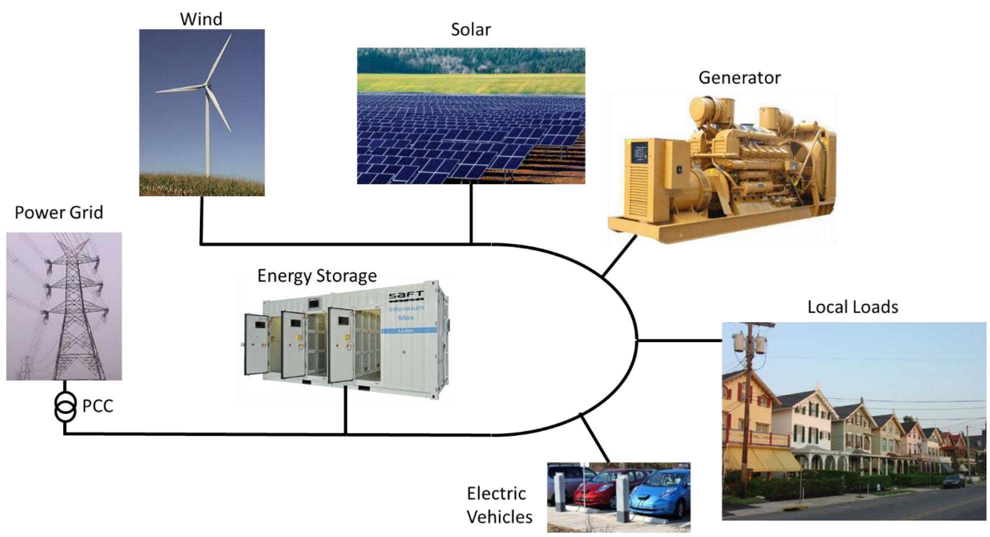

Figure 1: Example of a microgrid that uses data communication and edge intelligence to automate local power generation and balance against the power load. Microgrids help to integrate intermittent energy sources such as solar and wind.

The spread of DERs pose an additional challenge to grid stability. Renewable resources generate DC that needs to be converted to AC via an inverter. Conventional control algorithms assume there are strong voltage and frequency signals for inverters to follow on the main AC power line. Converting from DC to AC works well when the majority of the power is coming from traditional, rotating generators like a coal plant. But when the majority of the power is coming from DERs, the inverters' AC-following control algorithms fail as they chase the power signals from one to another. Consequently, DERs cause grid instability when they constitute more than 20 to 40% of the generation, depending on the grid design. Absence of strong AC signal on the power line is even more challenging for isolated ("islanded") microgrids based on renewables: without a power generator with rotating inertia to generate the main power signal in the microgrid, stability cannot be maintained (Obversely, a microgrid can isolate itself from the main power grid and run autonomously, immunizing itself from grid failures).

TECHNICAL APPROACH

To address the challenge of growing DER assimilation, Wipro, National Instruments, RTI and Cisco joined together to set up a Microgrid Testbed project under the Industrial Internet Consortium (IIC) to experiment with new approaches. The goal is to develop and demonstrate techniques for a 100% DER power-generation-based microgrid with sufficient intelligence to be operationally feasible and support a variety of business models.

A challenge for microgrids is to synchronize the voltage, and particularly the phase-angle, of the power in an islanded microgrid with the main grid in anticipation of reconnecting back to it. Reconnection can only happen when the phase angles of the two systems match closely. The simplest solution is to just shut off power on the islanded microgrid, reconnect to the main grid and then turn everything back on. To avoid losing power, microgrid controllers often use phase-locked loops or similar control methods to synchronize the microgrid power signal frequency and phase with the main grid's, but these methods are cumbersome and error-prone.

Newer methods use Phasor Measurement Units (PMUs), one on the microgrid side of the connection switch and one on the main grid side, to measure the AC signal phase angles of the two grids. Using local electronics, the system enhances the measurements with fast analytics to increase accuracy, and then passes it to the microgrid control system to adjust the phase angle of the microgrid to match that of the main grid for reconnection. However, the successful implementation of these methods depends on there being a rotating power generator in the microgrid that can be sped up or slowed to shift the overall phase angle of the microgrid. The DC DER generators then follow that main signal using their DC-to-AC inverters ("AC signal following"). This works when the rotating power generator is generating most of the power, but in a microgrid with more than 40% DC DER generators, a new, distributed control technique is needed with sub-millisecond synchronization.

Utilities have been slowly moving their proprietary communications infrastructure toward Ethernet transport and Internet Protocol (IP) or packet-based networks. We have used *time-sensitive networking* (TSN), the latest real-time Ethernet network between the inverter nodes to provide sub-millisecond synchronized measurement of phase, frequency and voltage. Instead of the traditional AC signal-following method, we used network communication to share real-time measurements of phase, frequency and voltage values. This let us create a virtual synchronization master and address the synchronization issue.

With these virtual synchronization capabilities, the frequency, voltage and phase angle of the microgrid can be controlled in real time to enhance the operation of the microgrid and facilitate the increased use of DERs. In addition, with a real-time secure data bus, enhanced visualization, advanced analytics and intelligent control over the associated inverters, battery storage and smart appliances, we can optimize and manage the operation of microgrids within the larger distribution grid, enabling new use cases and capabilities.

CONTROL AND VISUALIZATION OF MICROGRIDS

The three key capabilities of our microgrid-and-DER architecture are intelligent control at the edge of the grid, peer-to-peer, high-performance communications for local autonomy, and enhancement with third-party data and cloud analytics. We used a tiered architecture to integrate the edge, microgrid control and its real-time databus with cloud-based management, analytics and visualization (see Figure 2).

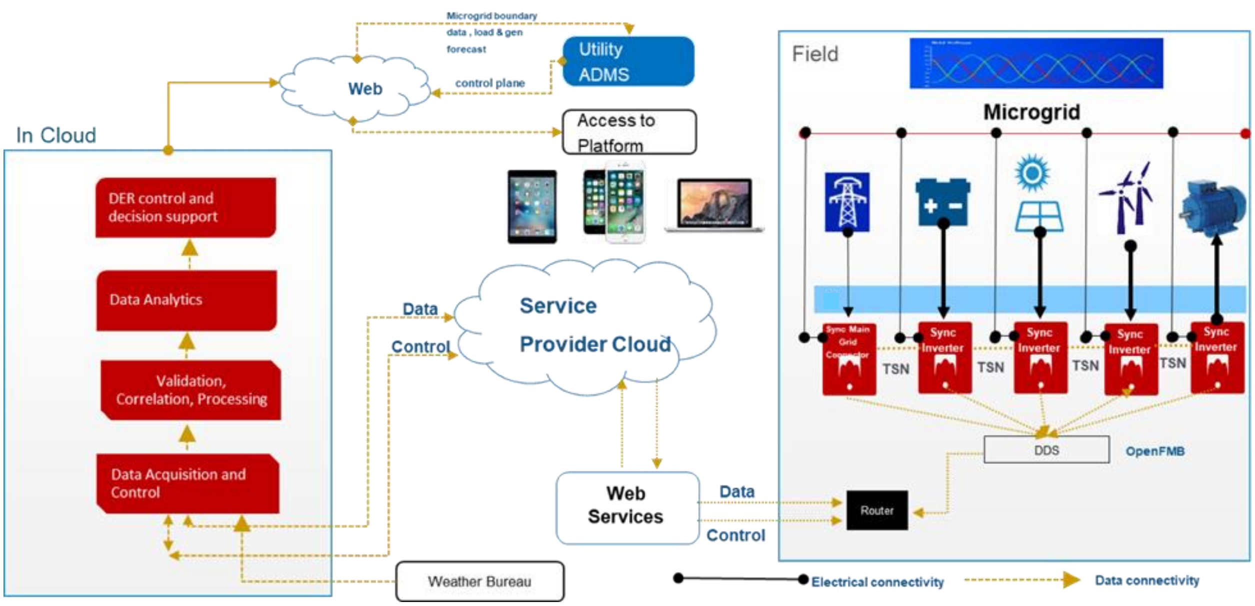

Figure 2: Deployed communication and control tiered architecture for microgrid and distribution grid management

With edge control and a real-time databus, microgrids can use batteries to provide interim power generation and smooth DER power fluctuations. A DER can produce a message within milliseconds when back-up energy is needed, so a local controller can switch the battery from charge to power-source mode. This keeps the local energy consumers powered and gives the utility time to spin up central power resources before the local system needs it.

TSN technology provides peer-to-peer, high-performance communications for distributed control systems that can synchronize and coordinate multiple inverters in a region by transmitting real-time measurements of grid power, frequency and phase-angle among inverters even as the DER penetration goes up to 100%. This distributed control technique for the inverters can shift the phase angle of a microgrid to match the main power grid in a short time. This greatly simplifies reconnecting islanded microgrids back to the main power grid.

The same connection is also used to gather data about the operating conditions of the grid and other deployed equipment continuously. We enhance and contextualize the collected data with other available third-party data, such as weather conditions. This allows us to perform intelligent analytics to estimate power supply and integrate with the local balancing authority for grid stability. We also integrate with utility back-end system to ensure full visibility and control of the operation of the grid, and provide an integrated dashboard for the distribution operator, microgrid operator, and in some cases, the end-users themselves (see Figure 3).

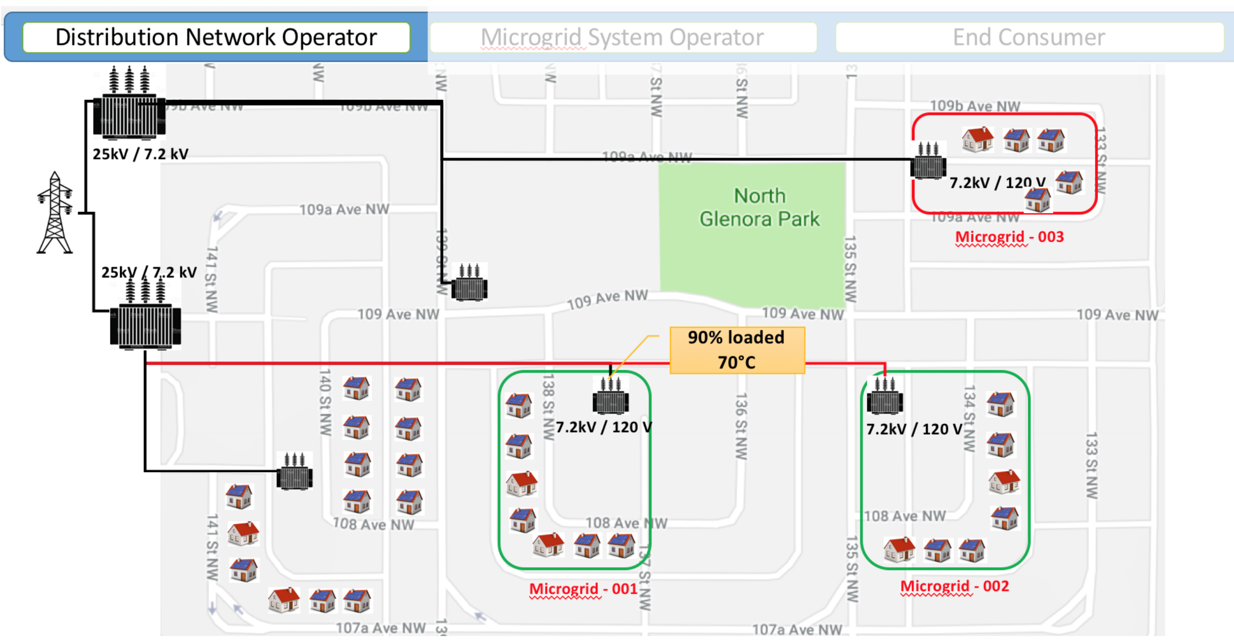

Figure 3: Distribution System Operator interface provides full visibility and control of a distribution grid with DERs and controllable loads

ENABLING A BETTER GRID

Additional data about the state of the grid, microgrid and DERs opens significant opportunities to optimize the power grid in addition to the synchronization and control issues. But intermittent renewable power generation still has these challenges:

- disturbances in the grid (e.g. voltage fluctuations),
- renewable generation not matching the load, which may cause frequency disturbances especially when the grid is operating on 100% renewables, or at times when the microgrid is isolated and
- requirements for spinning reserves due to the volatile nature of the renewables.

To eliminate these challenges, we need the microgrid to operate in a self-healing (closed loop) mode. It needs either to curtail the excess renewable generation or pick up the generation in real time without any inertia. There are two possible ways to manage this:

- Acquire the data and process it centrally. The system processes the information based on pre-configured algorithms and send the command back to the edge, to close the loop. This method allows full visibility into operations and complete optimization but suffers from delay in data transmission, often making the decisions obsolete by the time they reach the edge device.
- Acquire the data and process it locally. The system analyzes the data based on pre-configured algorithms running on each edge node (e.g. inverters) and closes the loop. This provides fast control, but not visibility into the system and its interaction with external components.

We chose to manage the closed-loop operations locally and enhance it with centralized analytics that allows access to complete system data and integration with external data. National Instrument's sync-inverters, connected with a TSN network, share the voltage and phase angle of the microgrid with the rest of the node inverters controlling the renewable generations, load and grid connection (refer to Figure 2). In case of any disturbances within the microgrid (e.g. loss of significant generation, switching in the excess generation or switching off the major loads), these sync-inverters follow the voltage and phase angle of the microgrid, and thereby work to balance the active power generation and load to avoid any destabilization of the microgrid, especially when islanded.

This also helps reconnect the microgrid back to the main power grid when needed because the voltage and phase angle of every inverter running within the microgrid can be adjusted easily. Further, the communication connection with the main grid, even while the electric connection is down, synchronizes the system to the main grid. This avoids a time-consuming process of synchronizing the microgrid with the main grid, and there is no need to shut down the microgrid before reconnecting.

The data from the sync-inverters is collected over Data Distribution Service (DDS) and exposed to the Wipro Cognitive Energy Intelligence (CEI) platform using RESTFul API's. The field solution supports an OpenFMB-based architecture and asset data model. The DDS protocol places an additional data-item by data-item layer of security over the network transport protocol security, ensuring that no critical data is exposed. The Wipro CEI platform monitors and controls these field devices in real-time or near real-time for common use cases such as advanced demand response, virtual power plant and price hedging (see Figure 4). Contextualizing sensor data, combining them with external data and machine learning enables allows us to visualize and predict generation and use it, for example, to control the charging and discharging of batteries, as well as control of smart appliances.

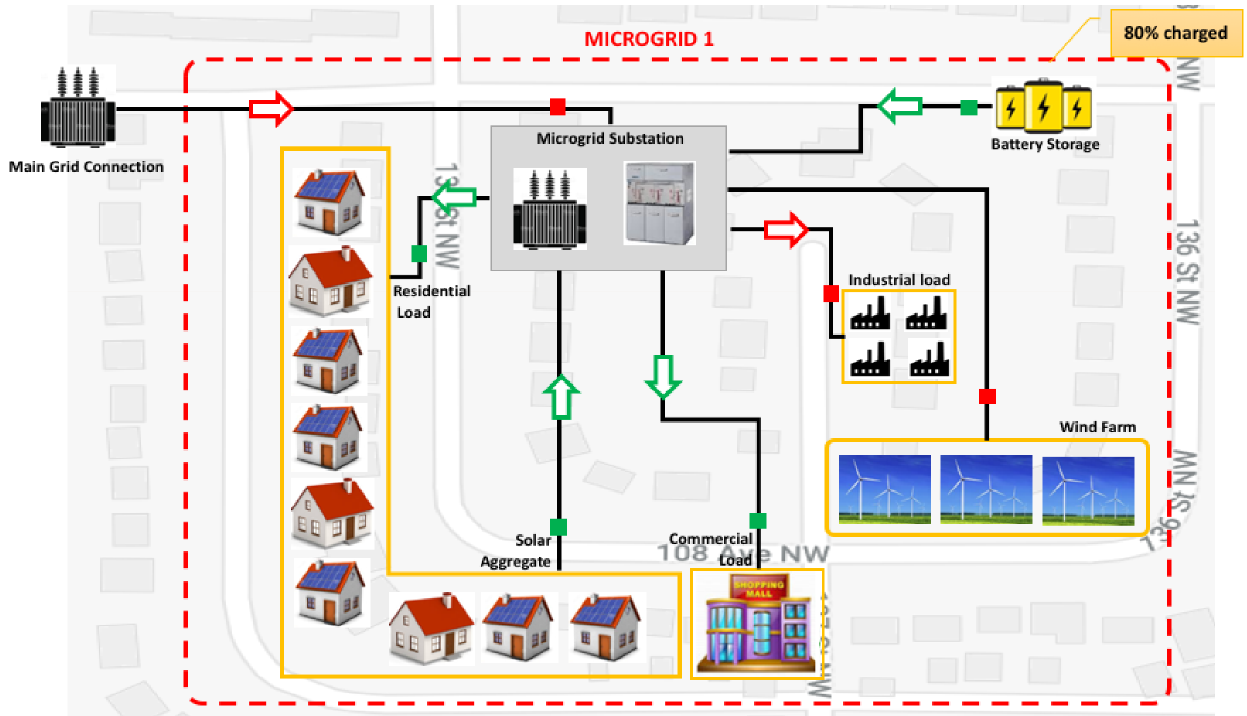

Figure 4: Microgrid Operator management interface allows field device monitoring and management

COMMERCIALIZING THE MICROGRIDS VIA THE IIC TESTBED

National Instruments, Real-Time Innovations (RTI), Cisco Systems and Wipro Limited have combined their expertise to develop a technically, operationally and commercially viable solution that meets real-world requirements. Creating a testbed under the IIC enabled collaboration with many industry-leading companies and gave us access to a comprehensive IoT technology framework. Now we can make the insights and findings from our research and innovation available to a broad range of the 250+ IIC-Member organizations.

To ensure that the system is interoperable and extendable and future-proof the design, we based our solution on the OpenFMB standard framework and data models that employ platform-independent configuration overlays to meet the diverse grid-hardware requirements. This combination of standardized data model, real-time databus and RESTFul API-based system let us create an adaptive visualization and dashboard for grid operational status and data analytics capabilities that can be easily customized to particular deployments.

The testbed has shown the power of this approach in National Instrument's IoT lab in Austin, where we could island and reconnect with the main grid for a microgrid based on 100% renewable resources. We also showed the ability to control adaptive loads. The availability of a real-time communication channel provided detailed data about the state of various components and allowed us to perform predictive maintenance. We can use the communication channel for adaptable control and to increase grid stability with better coordination with regional balancing authorities. By combining the grid data with third-party data, such as weather information and load prediction, more accurate prediction of future demands can be made, thereby giving enough time to start up fossil fuel generators as needed. The Wipro CEI platform offers advanced analytics capabilities, which supports intraday or longer forecasting of DER generation profiles, thereby allowing actions to suit various commercial programs and develop new sources of revenue without compromising the stability of the grid. This platform enables one to have more resilient and responsive demand response and auto-healing systems.

CONCLUSION

A research report[1] by the U.S. Energy Information and Administration (EIA) says that the generation of electricity with DERs has, so far, not been cost competitive, but with the continuing decreases in wind and solar costs, soon DERs will be cheaper than fossil fuel-based generation methods.

This makes microgrids with DERs increasingly commercially viable. Access, guaranteed availability, and military use also play important roles in microgrid deployments, and there are predictions of a dramatic increase in microgrid deployments in the near future. Many governments have launched inquiries into microgrid technology as part of their larger goals[2,3] and some citizen groups are working with utilities to explore neighborhood microgrid options.[4]

The promised benefit of renewables has not yet been truly realized, but the solution presented here makes increased renewable penetration possible by taking advantage of the latest development in embedded systems and communication technologies, and a technology-first approach to traditional problems. It enables microgrids that are truly competitive in terms of cost of per megawatt generation by addressing synchronization requirements effectively. By responding to external data, such as weather forecasts and real-time pricing and demand, this solution also mitigates some of the issues caused by fluctuations in demand and supply curves — an added benefit from its core functionality.

The utility business is undergoing major transformation in the wake of government mandates, changes to customer-demand patterns in the wake of electric vehicles and installation of on-premise renewable energy sources. Consequently, the generation, distribution and transmission operators must rethink their technical and business models to stay relevant and continue to keep the grid as reliable while having a feasible business model. By providing a unified communication technology among DERs and installed equipment, the solution presented here meets flexible business models and helps utilities manage their assets and networks optimally.

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This document is a work product of the Industrial Internet Consortium Testbed Working Group, authored by Dr. Manjari Asawa (Wipro), Brett Murphy (Real-Time Innovations), Sujan Bose (Wipro).

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