MICROGRID KNOWLEDGE SPECIAL REPORT

How Hardware in the Loop Addresses Challenges of Microgrid System Integration

Qiang Fu and Murilo Almeida, Head of Microgrid Application at Typhoon HIL, in front of Typhoon microgrid testbed at the Microgrid Conference.
Photo courtesy: typhoon-hil.com

brought to you by Typhoon HIL

Contents

Executive Summary

Microgrids play a key role in transforming the energy landscape. These agile local networks are a microcosm of power system evolution as they incorporate digital sensing, interpretation, and control to manipulate component and system behaviors with the goal of delivering greater efficiency, stability, and resilience. Microgrid projects, however, face several technical challenges that can impact cost and schedule performance. In particular, digital power systems require complex, active control; microgrids have limited system inertia; and vendor devices are evolving rapidly. Hardware in the Loop (HIL) testing and model-based engineering techniques provide an effective way to address these challenges, allowing project managers to bring project schedules and costs back on track.

Chapter 1: The Evolving Nature of our Electrical System

In the US, the centralized grid delivers electricity to around 145 million customers. This power originates in about 7,300 power plants and travels through 160,000 miles of high-voltage power lines and huge numbers of low-voltage lines to the consumers. That energy system, however, is becoming more complex with a much larger number of energy sources as well as diversifying players, roles, and even service offerings.

The traditional picture of large power stations supplying power to consumers is changing into an image with more distributed and decentralized features. Micro-generation and storage are on the rise, with consumers turning into “prosumers”. Industries and even private citizens are now producing, consuming, and storing energy to improve their own position; some sell energy back to their utility or via increasingly flexible exchange markets. The rising adoption of distributed energy resources (DERs), especially nature-driven wind and solar PV in place of fuel-powered generators, complicates maintenance of voltage and frequency stability and challenges established operating assumptions.

Fifty years ago, the Tennessee Valley Authority was still working to extend centrally generated power, from dams and even nuclear reactors, to American households. Today, utilities are expected to deliver abundant, reliable electricity on demand. As the 21st century plays out, people are relearning the fact that the world continuously changes, including how energy is generated and used. Energy projections are being reshaped in light of apparent climate impacts, which lead to weather related events such as fires and storms, interrupting distribution. Power systems are vulnerable to hackers attacking from anywhere in the world. The capacity to deal with these changes and uncertainty is known as resilience.

Resilience has moved on since the industrial era; it no longer means simply reinforcing and protecting systems to maintain their integrity through any hazard, such as wind and lightning. The modern day concept of resilience describes constructive ways to respond to events and changes of any kind, anticipated or not, by sensing, responding, learning, and adapting.

Resilience thinking provides motivation to find new ways to anticipate situations and have the flexibility to prepare and respond in ways that limit negative impacts, and incrementally change systems based upon newly recognized realities. It is no longer about emphasizing that all points in the electrical system have the same quality of service all of the time. Notably, resilience involves ownership of outcomes and initiative to manage them. This is one of the primary motivations for investment in DERs and microgrids: They provide the ability to anticipate, respond, and adapt, consistent with local needs.

Flexible, agile energy ecosystems

Today's microgrids employ fundamentally new technologies to create flexible and agile ecosystems. They network electrical devices and DERs in different combinations using a new generation of power electronic converters and controllers that manipulate electrical currents and voltages up to a million times per second to deliver power in the required form to the desired location at precisely the right time. Among other possibilities, microgrids can enable improved energy resilience, reductions in carbon emissions, and cost savings for the energy users. According to research carried out by Navigant, spending on microgrids is projected to increase five fold between 2018 and 2027. Spend is predicted to be on a combination of retrofits to existing infrastructure, and on brand new microgrids.

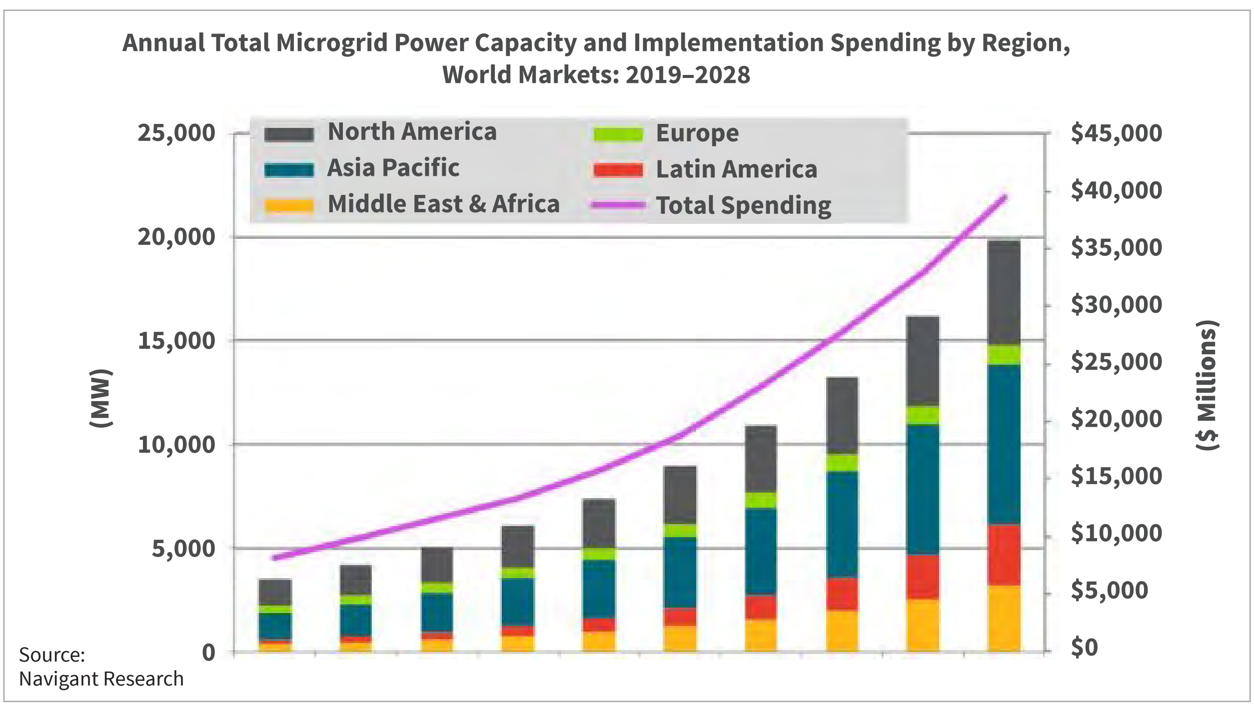
Unlike a generator in the basement of a building or a set of solar panels on the roof of a home, a microgrid acts as a management tool for a complex system of generation sources. Equipment can be turned on and off or ramped up and down to balance demands of the energy user with availability and cost associated with market patterns and changes in weather conditions. Energy storage can help manage such dynamics and enable the possibility to continue functioning when the larger distribution network fails.

Keys to this new trend are developments in power electronics, communications, and digital control systems, which have unlocked the ability for rapid data collection, analysis, and coordination between individual devices. Only updating existing power systems with faster, more efficient devices would result in marginal improvements in efficiency and reliability, as opposed to the ongoing transformation of the physics of networks. Just as digital communications replaced wires, switches, and tubes in analog systems with bits and packets, power electronics manipulate energy in digital form, thus dramatically increasing flexibility and agility.

Coupled with modern computing and communication technologies, the new digital power systems continue to become smarter and more capable. On the flip side, they are unavoidably complex. Digital power controllers simultaneously implement an expanding set of different functions that may themselves interact. Combining different devices, especially from different sources, introduces even greater potential for unanticipated behaviors and failures. This presents interoperability issues for those designing and building new microgrids, and retrofitters of new components into existing microgrids.

The increasing complexity can result in microgrid projects taking longer and costing more. According to research carried out by VDC in 2017, 43% of respondents to the Software and System Development survey reported that their embedded development projects were late.

Going forward, this is likely to become more exacerbated as embedded devices like power electronics converters become more interconnected and reliant on software for system functionality than the products they replace, leading to technical obstacles. In addition, once the microgrid is up and running, there is a risk that it will not run in an optimized way. Steps to mitigate these risks do exist, through the validation and certification of microgrids.



Chapter 2: Design and Validation of Microgrids

Before investing significant sums of money, a prospective microgrid owner or operator needs to explore the value proposition. Based upon desired system behaviors, such as uninterrupted operation of mission critical equipment or maximizing utilization of renewable resources, engineers scope and design a system concept. The question is, will the real system actually perform efficiently, flexibly, and reliably? Traditionally, those answers have been discovered during and after installation, long after the opportunity to "get it right the first time".

Microgrid customers could view a version of their future system in validation centers such as Rolls Royce's Friedrichshafen site in Germany, which demonstrates microgrids in operation. This gives some initial assurance, but it is an operational snippet and does not demonstrate the full range of behavior of the system. Microgrid components and systems must also pass certain certification and validation tests before they are allowed to connect to the grid and operate.

As an example, an emerging microgrid interoperability standard, IEEE 2030.7 and IEEE 2030.8-2018, specifies test procedures for verification of microgrid controller performance. The standard aims to present metrics for a comparison of the control functions required from both the microgrid operator and the distribution system operator (DSO).

New as well as existing microgrids face similar issues. If new components are added to an operational microgrid, testing must be carried out to ensure these are properly integrated. The new components must be able to "talk" to the rest of the system, enabling it to function effectively and safely. In addition, certification requirements can change over time, so microgrids may need to undergo recertification during their lifetime.

It is prudent to test ideas and designs as early as possible to give a microgrid the best chance of success, and continue testing throughout the lifecycle, to ensure the system can deal with faults and pass validation and certification requirements.

Chapter 3: Hardware in the Loop (HIL) – Tried and Tested

These tests can be carried out with real power equipment in a lab environment, such as the National Renewable Energy Laboratory's (NREL) megawatt scale Energy Systems Integration Facility (ESIF). This federal laboratory allows manufacturers and integrators to test technology at actual power before implementation. But equipment can be damaged, in some cases multiple times before passing the test, making it a time consuming and costly process. In addition, power labs are inflexible and cannot be easily configured to resemble real-life microgrid operational scenarios, hence limiting their usefulness.

Offline digital simulations can be built ahead of lab testing to provide some assurance over results, but these lack fidelity. By definition, they are simulations where control and communication are often modeled using significant simplifications and abstractions. This is where Hardware in the Loop, or HIL testing, plays a role. Using HIL, physical controllers running actual software and firmware can be connected to a digital, real-time simulation of a microgrid power stage, the power processing part. Testing equipment and software in a simulated environment increases the fidelity, as these tests more closely resemble reality.

HIL testing is a well-established technique for the design and testing of complex systems, such as those found in the aviation and car industries. A new car contains many digital control units that must seamlessly interact with each other. Cameras, radars, driver assistance systems must all be tested together before the final product is complete. When a driver puts their foot down on the accelerator, the engine's electronic control unit converts sensor measurements to increase the vehicle's air intake. In a HIL test, the engine is replaced with a simulation. The control unit is tricked into thinking the engine is present, passing on signals.

Each electronic control unit of the car can interact with thousands of simulated use cases in the HIL testing environment. This pushes the control units to their limits and allows the system integrator to resolve software defects before they reach the final assembled product. This is achieved without the time and cost associated with physical testing.

More recently, HIL testing has been applied to power systems. The IEEE's P2004: Hardware in the Loop Simulation Based Testing of Electric Power Apparatus and Controls, approved in 2017, establishes simulation development practices and HIL-specific documentation, verification and validation. It also serves as a platform to promote HIL testing and educate the industry about this method.

Depending on the type of device under test, HIL testing can be classified into different categories:

- P-HIL: If the device under test is power apparatus, connected to a simulation of the rest of the system, it is referred to as a power-HIL or P-HIL simulation. This type of testing gives high fidelity, at lower costs than a full power test.
- C-HIL: If the device under test is a controller, it is referred to as a controller HIL or C-HIL simulation. Again this can provide high fidelity, at lower costs than a full power test or P-HIL.

Chapter 4: HIL and Microgrids

The IEEE's 2030.8-2018 Standard for the Testing of Microgrid Controllers recommends C-HIL as an appropriate method for testing microgrid controller functionality, such as islanding and dispatching. The controller is difficult to model realistically, but it's often easier and cheaper to modify than the rest of the hardware. As such, organizations like Typhoon HIL apply high fidelity C-HIL methodologies by putting physical controllers into HIL devices and connecting them through HIL-connected interfaces.

Up until now, real-time simulation has focused on transmission, but it is becoming more commonly used in distribution systems and for microgrids. HIL testing de-risks the process of designing, integrating, and configuring the piece of hardware under test, such as microgrid controllers or protective relays.

According to Ryan Smith, chief technology officer at EPC Power, the power electronics converter company relies on C-HIL testing. EPC Power uses C-HIL testing to develop and test their battery storage inverter controller software. Their software development team continuously tests software to verify performance and specification with C-HIL.[1]

EPC Power also provides system integrators with its *HIL Compatible* inverter model, which can run in real-time. System integrators can use this model to perform virtual system integration, verify system performance, adjust protection settings, and test different faults conditions.

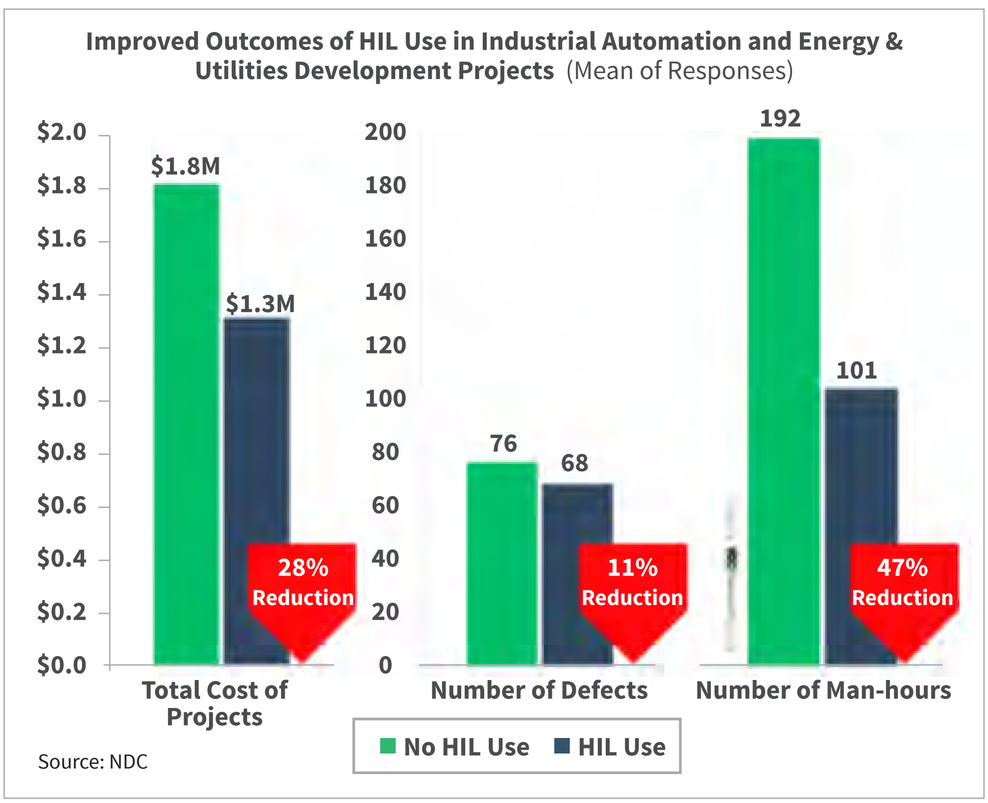
Scott Manson, technology director at Schweitzer Engineering Laboratories, raises a learning and development opportunity for engineers. Indeed, a C-HIL testbed is a high-fidelity "flight-simulator" for microgrids. An engineer working with a HIL system can deal with a "lifetime of career experience consolidated into a week," experiencing thousands of diverse faults during testing.[2]

When it comes to the cost of developing HIL models, the size and complexity of the microgrid play a role. In general, if the microgrid is in the megawatt scale and contains a diverse range of DERs, HIL can be a cost effective investment. Some business models are shifting towards HIL as a service, simplifying the process. For a military application using their microgrid as a back up for mission critical applications, a high value is placed on the assurance that the system will work under any fault condition or in any scenario, which can be provided by exhaustive HIL testing.[3]

Those already using HIL testing do experience benefits. According to research carried out by VDC, respondents who used HIL reported a mean reduction of 28% in total project cost and reduction of 47% in the number of associated man-hours.

In addition, VDC's survey showed that projects using HIL testing were more likely to be on or ahead of schedule than those not using HIL. They were also able to produce systems with an average of 42% more lines of code, and experienced a 38% reduction in software defects in the deployed product.

Taking this into account, it is clear that applying HIL methodologies to microgrid projects not only improves system integration, but the overall delivery of the project. Even further improvements were reported to VDC by projects that used a combination of HIL and Model Based Engineering.



[1,2,3] Microgrid 2019 Typhoon HIL session

Chapter 5: Typhoon HIL and Model Based Engineering

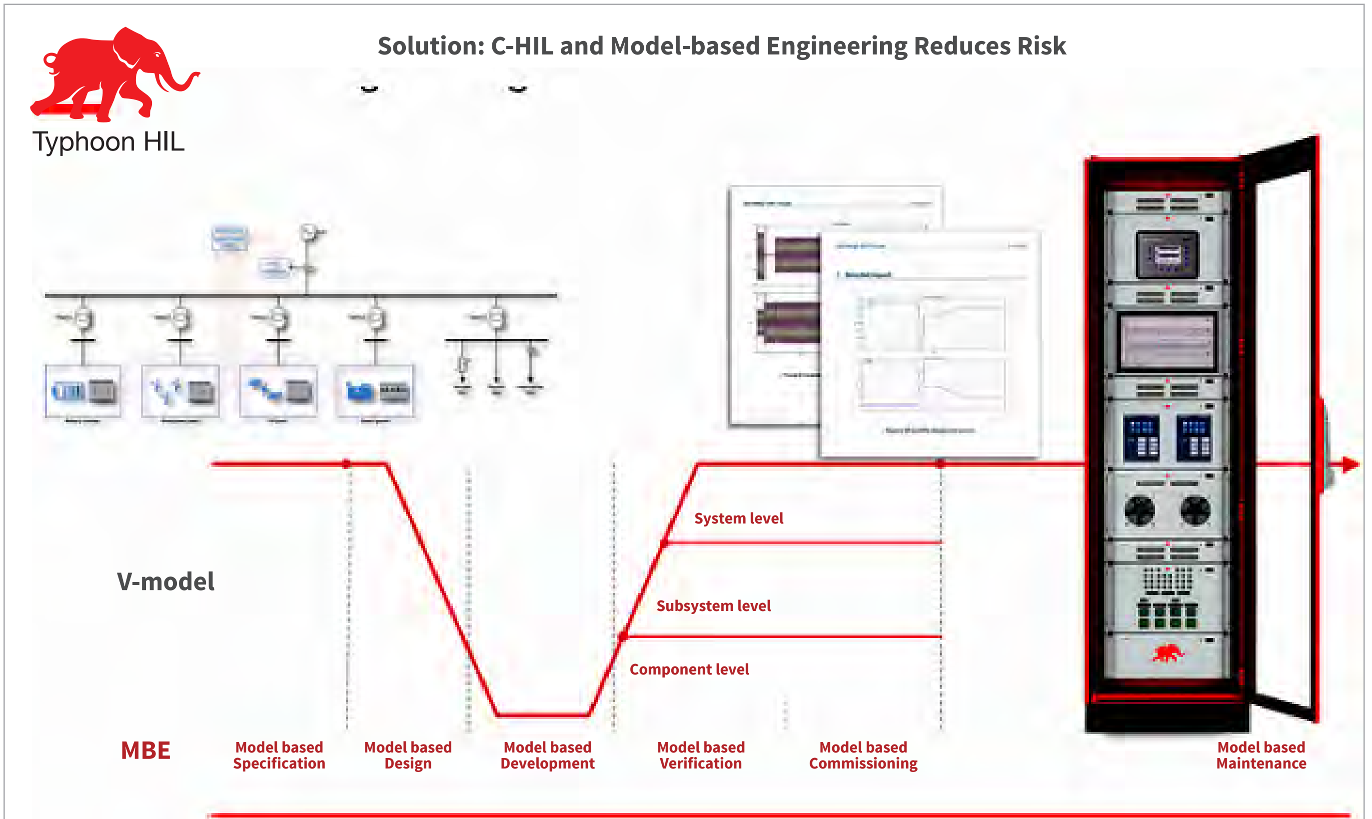
The current approach to microgrid development tends to be disconnected, with various teams taking responsibility for the different stages of the development life cycle. The nature of the approach allows these groups to make decisions independently of each other, leading to error and inefficiency. Teams modeling the microgrid may not fully take into account the techno-economic assessment or the safety requirements of yet another group. Operational teams may not be consulted until it is too late to take their future maintenance issues into consideration.

Typhoon HIL promotes a model-based engineering (MBE) approach to microgrids by representing the system as an integrated digital model, facilitating examination of system performance and archiving documentation. The integrated digital model can stay with the microgrid throughout its life cycle, from specification through to operations, eliminating the risk of losing knowledge, decisions, drawings and documentation further down the microgrid's life.

The MBE approach can streamline microgrid development. Existing Typhoon HIL schematics assist with the initial configuration; different components can be dragged and dropped from the library into the model to customize the system. At any stage, the designer can run a simulation of the system with generic or increasingly refined specific model parameters. The Typhoon HIL system allows portions of the virtual model to be interchanged with actual physical controllers running interactively "in the loop."

An ultra-high fidelity HIL simulation allows the teams involved with design, economics, safety, commissioning, and operations to contribute to a single database or model of the microgrid and examine different aspects of system functionality in the bigger picture. In addition, model-based design simplifies communications between diverse design teams by virtue of being an executable specification. This means users can learn about the model by running it, especially if it is not initially clear what the model does.

Model-based design improves system integration by maintaining a single shared system model. In combination with C-HIL, it reduces project risk by providing the opportunity to simulate iteratively both the higher-level system and more specific component behaviors as design details evolve through the microgrid development process.



Source: Typhoon HIL article

Specification

Defining the requirements from a microgrid and putting together a suitable specification at an appropriate cost to suit the customer's needs is one of the early steps of every microgrid project. Rather than only showing drawings and documents of the microgrid configurations, it is possible to use Typhoon HIL's MBE approach to create executable specifications or interactive digital models of the solution with varying levels of fidelity.

> Testing of interoperability in a C-HIL environment rather than a power lab with real high voltage equipment reduces costs and risks and improves overall quality since the test coverage, or the number and range of tests, is significantly higher.

Sales teams can use these dynamic replicas to demonstrate operational and financial benefits to prospective new clients. Sizing and virtual testing provides early realistic ROI and OPEX assessment, enabling smart investment decisions. Test driving the microgrid in this "flight simulator" months or years ahead of building the real microgrid can be a game changing, immersive experience for buyers and investors.

This is also an opportunity to address the increasing costs of energy storage and DER integration, recognizing that interoperability may become a problem later in the design cycle, as different devices may fail to "talk" to each other. Testing of interoperability can be carried out from day one. Doing this in a C-HIL environment rather than a power lab with real high voltage equipment reduces costs and risks, and improves overall quality since the test coverage, or the number and range of tests, is significantly higher.

Design and development

Testing continues as designs narrow down from the system level to the component level. This applies to new microgrids or the addition of components into existing systems. Typhoon HIL's software provides an extensive library of industry-standard HIL Compatible components, as well as HIL compatible physical controllers that can be plugged into the simulated environment, mimicking real life.

The design process begins by defining the specification, with accompanying tests, carried out continuously from the earliest design stages. The microgrid control and protection system can be interfaced directly with a high-fidelity model of the microgrid power stage and put through its paces by testing under faulty conditions. Model based engineering and model based testing reduces risk in later stages, such as commissioning, where additional days on site can add significant costs to the project.

Assessing the behavior and performance in the virtual environment minimizes the risk of purchasing suboptimal and incompatible components. Also, testing all communication protocols, such as ModBus, IEC 61850, and IEC 614000, between any devices in the microgrid can eliminate interoperability issues.

Verification and commissioning

After testing the individual system components, going back up to the system level, Typhoon HIL's C-HIL testbed can be used to carry out power automation testing. The real controller is connected to the simulated environment for testing under all faulty conditions, grid code and certification requirements. Physical controllers can be used to operate DERs and breakers, with their official software and firmware releases.

Precertification can be carried out in-house, prior to interaction with the certification body. Typhoon HIL has an extensive library of automated tests that can be used to validate the system against common standardized tests, such as IEEE 2030.8 and the Modular Energy Storage Standard (MESA).

Extensive testing will give confidence when entering the commissioning stage. Test coverage with a C-HIL testbed is an order of magnitude larger than lab based power tests. Unexpected system behaviors become less probable, and the process is more likely to run on time and to cost.

For a component manufacturer, it is beneficial to provide a prepackaged HIL compatible model to a system integrator, who can plug-and-play into the HIL simulation. This can make the design and verification process easier for a system integrator, as HIL compatible components and controllers can be prevalidated and precertified.

Maintenance

Typhoon HIL can support lifetime operations of the microgrid. It is plausible that the system will be expanded or upgraded through the addition of new components during its life. Without a digital model of the microgrid and HIL testing, guaranteeing these new components will integrate smoothly without creating unexpected faults is difficult.

It is, however, possible to set up the digital model in the HIL environment and run a digital twin. Any new components can be added to the digital twin, and extensive testing and validation can take place prior to physically adding the component. This de-risks the process and provides assurance to the microgrid operator.

The digital twin becomes "living documentation", not only for future modifications and retrofits, but also for software updates that are often mandatory to maintain cybersecurity compliance. These can be trialed before rollout on the real system.

Chapter 6: Case Studies

CASE STUDY 1: Duke Energy | *Increasing confidence with HIL testing*

Duke Energy, providers of microgrid solutions since 2013, decided to start using HIL because they did not want to learn by making mistakes on real customer circuits. Prior to HIL, the organization used open loop static based simulations such as Simulink, but found large discrepancies between the performances of actual equipment during validation tests against the open loop models. This is not to say that HIL models are immediately 100% accurate, but the closed loop system allows feedback to be used to fine-tune the HIL models.

"Once that piece of equipment is validated in your HIL, your confidence is high, but there's an upfront process to get through. The hope is once you have that repository of different building blocks, future deployments of future systems should benefit." *Stuart Laval, Technology Director, Duke Energy*

For the time being, microgrids are custom-made, as they must integrate into existing power systems and coordinate with protection devices. DER, inverter-based systems present different challenges to synchronous generators, such as the design of effective grounding, protection and control.

For a microgrid with a mix of DERs, the battery becomes critical for managing islanding, synchronizing with other DERs and the grid system. As the battery becomes the focal point, its business case has to be justified, with additional value coming from the provision of grid services. As such, there is a requirement for the ability to island and reconnect seamlessly. This leads to the need to understand fault responses of inverters in power electronics-based resources in grid connected and islanded modes, which is where HIL testing comes into its own.

HIL testing allows Duke Energy to build full, closed loop systems and model the fidelity of PID controllers of inverters to understand the fault response with transience on the grid and existing control schemes. Duke Energy found that HIL gives a better picture of system dynamics, without impacting customers because it is done off the grid in a lab environment.

"Utilities have built microgrids without HIL, made technology decisions blindly without understanding full system dynamics. HIL would have provided value and helped with understanding the use cases and impact from a protection control perspective." *Stuart Laval, Technology Director, Duke Energy*

Looking ahead, Duke Energy is developing "cookie cutter" scalable, repeatable microgrid components, and says that HIL is a "no-brainer" for this. HIL becomes an under-the-hood, digital twin for these plug-and-play microgrids. New algorithms can be trialed and new control schemes can be validated before roll out for the customers. Site testing and de-bugging of software can also be completed ahead of deployment.

There is, of course, an upfront investment and process for the use of HIL. For Duke Energy, which develops many microgrid systems, this is worthwhile. HIL provides vital understanding of how equipment will integrate with existing power systems.

CASE STUDY 2: Rolls Royce | *Reducing surprises in the field*

Rolls Royce Power Systems, a system integrator, runs microgrids across the globe. They originally set out to deliver plug-and-play storage solutions to enable customers to integrate solar power and wind, but realized that for this to work they had to deliver microgrid controllers. A centralized controller was developed; the same controller for every microgrid, with an abstract model of the different possible DER assets to allow customization for different microgrid setups.

Initially, Rolls Royce carried out microgrid integration testing at a demonstration facility. A prototype battery system, a genset, and other items of equipment allowed quick results to be gathered. With around 50 running microgrids in the field, a growing customer base, and increasing complexity, testing at the demonstration facility became impractical. The alternative option, testing in the field, carried too much risk for the customer. As such, Rolls Royce sought a better solution to ensure equipment was correctly integrated and the control system worked as expected, and HIL fit the bill.

As system integrators, Rolls Royce takes off-the-shelf items of equipment and brings them together to make an AC coupled battery storage system. This is then integrated with the whole microgrid, and Rolls Royce ensures all the different parts work together.

"Documentation is only a start when you work with these components. You always learn something new in the field."
David Dunnett, Head of Software Development, Rolls Royce

Using HIL testing allows Rolls Royce to reduce surprises in the field, making commissioning easier and faster. With customers in Indonesia, Haiti, and Greenland, to name a few locations, reducing surprises also helps to cut travel time and cost for engineers and technicians.

"We have a long list of existing energy equipment that we can already talk to, control and support, but every time we add a new one, you're adding uncertainty and risk. We want to make sure that everything is still working as it did before."
David Dunnett, Head of Software Development, Rolls Royce

Real-time simulations of components, coupled with the actual controller, create a mock interface for running a variety of test cases. This allows Rolls Royce to carry out regression testing of the control software, providing confidence that updates can be deployed on older systems, and new features can be added without breaking old ones.

CASE STUDY 3: Hitachi ABB | *Complying with standards*

Successful integration of energy storage and renewables into a microgrid demands management of competing project requirements. Hitachi ABB's 200 installations across the world, from the deserts of Australia to the icy Arctic, and a technology platform with 30 plus years of legacy, are an advantage for the organization. It reduces the likelihood of mistakes with system configuration, deployment, and operation, and allows them to juggle competing requirements.

> By deploying a 30 MW/ 8 MWh battery energy storage system on a long radial feeder line, the project has reduced unplanned outages from eight hours to under 30 minutes for the customers connected to the network.

But the wealth of experience is not enough; Hitachi ABB needs to prepare for the unknown. As such, they pair these capabilities with HIL modeling and testing to ensure microgrids are the right fit for the market. This starts from day one; simulations are used in the creation of the business case for the customer. Real-time HIL platforms help to optimize the design and service offerings for Hitachi ABB's portfolio.

"Being able to test the desired functional concepts of a microgrid prior to deployment is a major factor in de-risking a project." *Tilo Buehler, Global Product Manager, Grid Edge Solutions, Hitachi ABB*

State of the art modeling and simulation were used for the ESCRI-SA Dalrymple project in Australia. By deploying a 30 MW/ 8 MWh battery energy storage system on a long radial feeder line, the project has reduced wind production curtailment from the 91 MW Wattle Point wind farm. It has also reduced unplanned outages from eight hours to under 30 minutes for the customers connected to the network. In the first six months of operation, it has created over AUS $50 million in revenue from frequency control ancillary services. The success of the project was enabled by the use of HIL testing.

Hitachi ABB also applies HIL testing to comply with certification and standards, such as grid codes, prior to deployment. Coupling a battery energy storage converter controller with a real-time HIL system allows the team to check its behavior against country specific test cases. A large number of tests are run against flexible conditions to meet the requirements of a specific customer or country.

"This is a great benefit in managing timescales, managing cost of validating the system performance and thereby a benefit towards the certification." *Tilo Buehler, Global Product Manager, Grid Edge Solutions, Hitachi ABB*

Conclusion

Microgrids are playing an important role in the ongoing energy transformation, but the advancement of power electronics components and systems creates integration and interoperability issues. Model-based engineering and C-HIL open the door to high-fidelity testing of microgrids against extreme system faults, expensive or sometimes impossible to create in power labs. This is giving microgrid system integrators assurance which is different components of the microgrid will operate seamlessly, and microgrid operators are gaining peace of mind, knowing that their system will behave as expected when the unexpected happens.