Transforming the Grid's Architecture: Enterprise Control, the energy Internet of Things, and Hetero-functional Graph Theory

Steffi O. Muhanji, Wester C.H. Schoonenberg, Amro M. Farid

I. Introduction: The Evolution of the Grid's Architecture

The electric power grid was developed on an implicit architectural assumption of centralized dispatchable generation serving all of customers' passive distributed loads irrespective of the operating costs required to do so. However, several new energy management change drivers are emerging to uproot this status quo:

- the rising demand for electricity,
- the emergence of distributed renewable energy resources,
- the emergence of electrified transportation,
- the deregulation of power markets, and
- innovations in smart grid technology.

Responding to these drivers requires new and integrated technical solutions for energy management. This work identifies three such technical solutions: enterprise control, the energy Internet of Things, and hetero-functional graph theory. First, ***enterprise control*** is an analytical technique borrowed from the manufacturing sector that states that in order to achieve synergistic techno-economic performance, a large complex engineering system must be simulated and assessed in terms of not just its physical layer but also its many layers of market operations and control. Second, the ***energy Internet of Things*** (eIoT) provides a technological solution for activating tens of millions of physical devices at the grid's periphery so that they can be potentially orchestrated into demand response schemes that participate in energy markets and provide essential ancillary grid services. Finally, ***hetero-functional graph theory*** recognizes that, as eIoT takes root, it does so at the interface of multiple interdependent infrastructure systems. Consequently, the graph-theoretic analytical techniques often used in power systems engineering have to be extended to explicitly account for the heterogeneity of function that these devices offer.

The purpose of this article is two-fold. First, it describes each of these technical solutions; be they technological or analytical. The technological solution of eIoT constitutes a type of grid transformation. Meanwhile, the analytical solutions of enterprise control and hetero-functional graph theory serve to guide and inform grid architecture transformation decisions. Second, the article serves to describe the benefits of each of these technical solutions particularly as they address the change drivers identified above.

To facilitate the discussion on grid architecture transformations, an architecture is a structure defined to have the following elements:

- A system boundary
- A set of elements of form; be they physical or informatic in nature

- A set of elements of function that together describe what the system does
- A set of interfaces or interactions between these elements
- A description of which functions each formal element does

Consequently, an architectural transformation constitutes a change in one or more of these sets.

II. Enterprise Control

A: What is enterprise control?

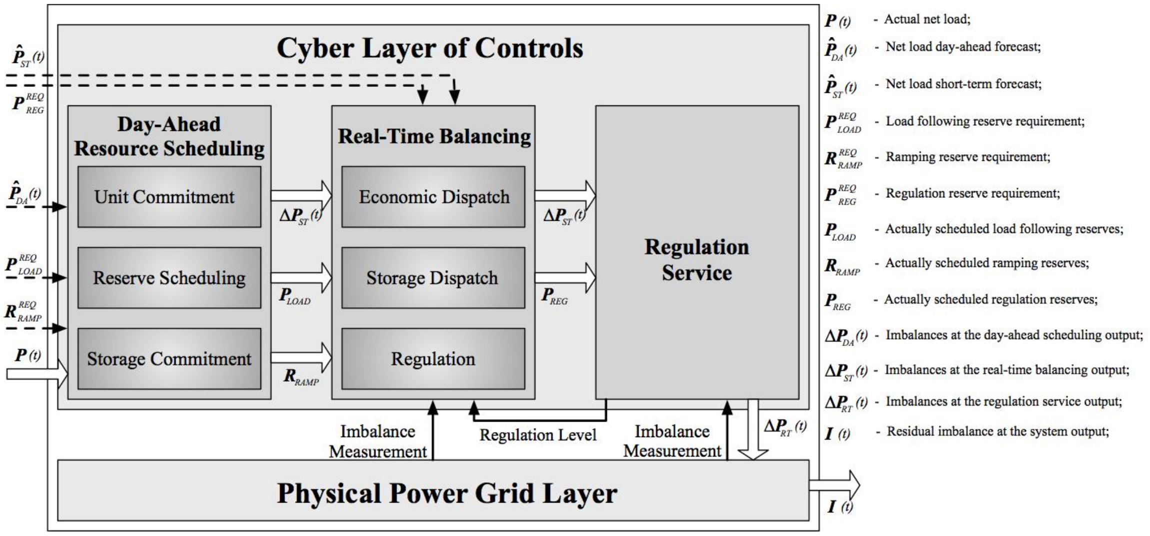
The concept of ***Enterprise Control*** originated in the manufacturing sector where it was recognized that in order to simultaneously meet the technical and economic objectives of the shop floor, it was necessary to integrate and ultimately simulate the many decision-making, automation, and control structures of the enterprise. Automation became viewed as a technology to not just manage the fast dynamics of manufacturing processes but also to integrate that control with business objectives. Over time, this recognition led to the development of several enterprise control architectures that eventually coalesced into the current ISA-95 standard, which defines in detail an abstract model of an enterprise including control functions, business functions and their information exchange. Analogously, recent work on power grids has been proposed to update operation control center architectures and integrate the associated communication architectures. The recent National Institute of Science and Technology (NIST) interoperability initiatives further demonstrate the trend towards integrated and holistic approaches to power grid operation.

Although the Enterprise Control ISA-95 standard does not specifically define the term, in the context of this work, enterprise control is the ability to combine ***all*** of the decision-making, automation, and control structures of one or more organizations so that the combined enterprise simultaneously meets its economic and technical objectives. This ability requires the harmonization of real-time physical control with often slower economic control so as to achieve a closed-loop techno-economic control. More specifically, the ISA-95 standard defines the scope of and the interfaces between enterprise and control systems for industries governed by batch, continuous, and discrete physical processes. Enterprise control is not a specific type of control law like robust control or optimal control. Rather, every enterprise, whether explicitly stated or otherwise, has a techno-economic control structure of some kind, regardless of how effective its technical and economic performance is. The concept of enterprise control is to integrate the underlying control functions so that the holistic performance improves to simultaneously meet economic and technical objectives. Given the complexity of this integrated enterprise control structure, enterprise control ***simulation*** is often necessary as an analytical decision-support technique.

In this context, the LIINES (Laboratory for Intelligent Integrated Networks of Engineering Systems) began to apply the concept of enterprise control to electric power systems in what we call Electric Power Enterprise Control Systems (EPECS). The goal was to bring an integrated and holistic approach to simultaneously managing the technical and economic objectives of the grid as its architecture transforms. Such an enterprise control approach is in contrast to the typical practice in power systems where distinct models (e.g. frequency stability, small-signal stability, transient stability, voltage stability, power flows, real-time market behavior, day-ahead market behavior) are used independently for assessment. Instead, the concept of enterprise control recognizes that every control decision has the potential to have both physical as well as economic implications. Recognizing such couplings requires that any control decision be assessed within the context of its technological value as well as its cost implication. This integrated approach allows us to simultaneously reduce the investment costs of newly installed technologies, realize operational savings with new market mechanisms and control algorithms, all while enhancing the grid's overall technical reliability.

As in the case of enterprise control generally, electric power enterprise control system is not a specific control algorithm. It simply reflects the techno-economic control structure of the chosen electric power enterprise. For example, when enterprise control is applied to a traditional North American electric power transmission system, it may have a structure similar to the one depicted in Figure 1. A day-ahead energy market, real-time energy market, and regulation service sit on top of a physical power grid layer so that changes in the parameters of any of the four layers result in changes in both technical and economic performance of the system. Such a structure can be further customized to address the specifics of an electric grid in a particular region (e.g. New England). In recent EPECS research, the structure shown in Figure 1 is simulated with mathematical models of the physical power grid, regulation, and the day-ahead and real-time energy markets. Furthermore, and of primary relevance to this article, the enterprise control structure can be evolved to fundamentally understand the grid's techno-economic behavior as its architecture is transformed.

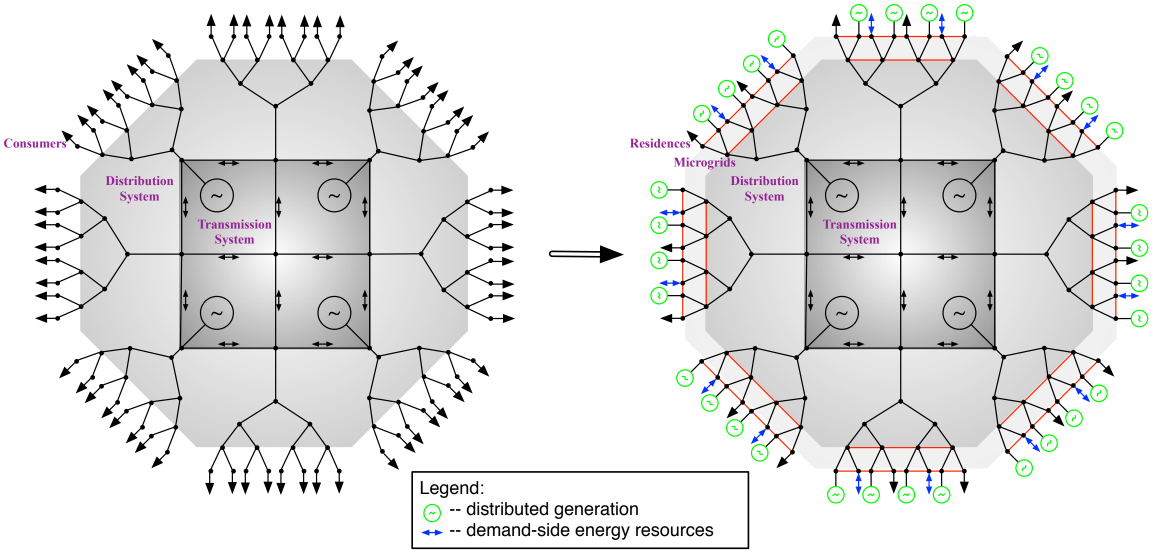
Figure 1: The electric power enterprise control system (EPECS) simulator block diagram



B: Why do we need electric power enterprise control?

Ultimately, electric power enterprise control is needed to facilitate the transformation of the grid's architecture. As variable energy resources (VERs), energy storage resources (ESRs) and demand-side resources (DSRs) take root in the electric power grid, they fundamentally transform the grid's structure and behavior. For example (as in Fig.2), the distribution system was structured for the one-way flow of power from the transmission system to end users. As more consumers start to produce their own electricity from distributed (renewable) energy resources, the distribution system may be forced to evolve to allow power flows in both directions. Such a physical change also requires major changes in how the electric grid is managed and controlled. Enterprise control simulation provides a means to assess holistic techno-economic behavior of this integrated system throughout this ongoing transformation.

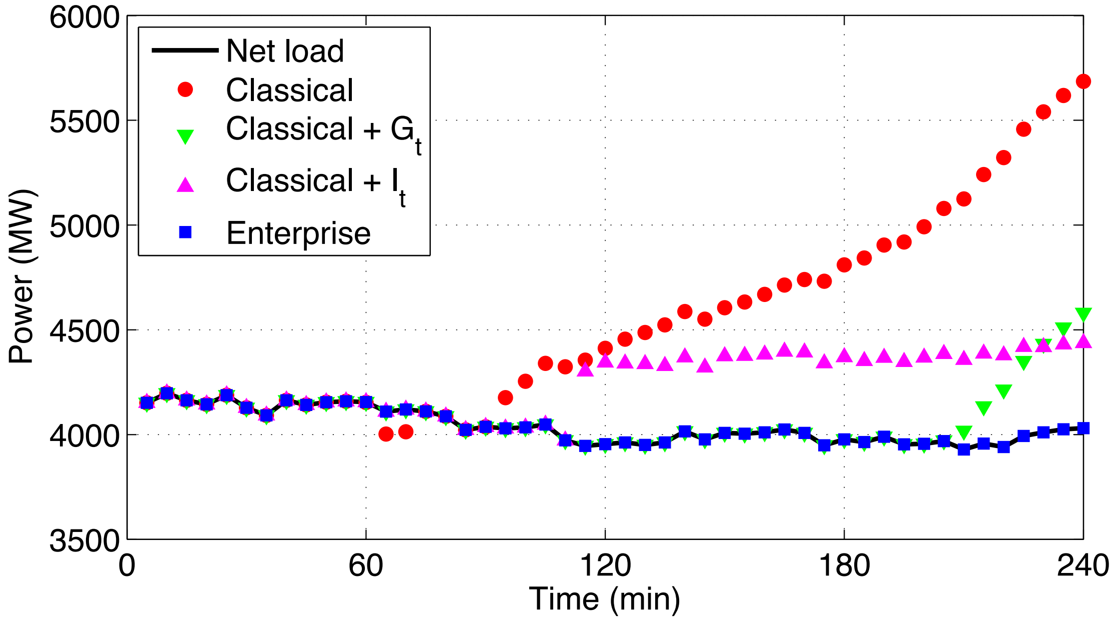
Figure 2: A conceptual transition for a traditional electric power grid to a future smart grid with a two-way flow of power and information.



The integration of VERs is fundamentally a multi-timescale phenomenon that affects the grid's many layers of decision-making and control. Nevertheless, the predominant practice in the power systems operations and control literature is to treat each of these layers strictly independently. Primary control addresses transient stability phenomena in the range of approximately 0.1-10s. Generator output adjustments on this timescale are performed by the implementation of local automatic control techniques such as automatic generation controls, and automatic voltage regulation (AVR). Secondary control, at the minute timescale, resides within the operations control center and fixes the set points for these automatic control techniques. Finally, tertiary control occurs at the time scale of tens of minutes or hours and, in many regions, implements the market structures mentioned above in Figure 1. The long-standing and practical assumption that each control technique can be studied independently is challenged by VER integration.

In this regard, electric power enterprise control simulation has demonstrated the benefits of assuming interdependent power system operations layers. In Figure 3, the block diagram shown in Figure 1 was simulated under four conditions: 1.) no feedback back to the real-time balancing layers (labelled as “classical” in red circles), 2.) feedback of grid imbalances (labelled as “classical + I_T” in purple triangles”, 3.) feedback of regulation level (labelled as “classical + G_T” in green triangles) and 4.) feedback of imbalances and regulation level (labelled as “enterprise” in blue squares. The simulation results show only the fourth condition demonstrates stable behavior that accurately tracks the system net load. Such results would not be visible from a traditional single-layer power system model (e.g. frequency stability). The inclusion of multiple timescale layers in a simulation provides an analytical means of understanding the techno-economic trade-offs that emerge from VER integration. Most fundamentally, VERs typically reduce production costs in energy markets but increase simulated imbalances. These imbalances can be mitigated by changes in the required quantities of load following, ramping, and regulation reserves or the energy market time steps; which in turn affect the energy market production costs. Quantifying these trends through simulation has served to methodologically advance the VER integration literature. More recently, and as mentioned further below, EPECS simulation has been demonstrated in a full-scale case study in the ISO New England System Operational Analysis and REnewable Energy Study (SOARES).

Figure 3: The impact of four types of real-time energy market cross-layer feedback laws on the electric power system’s balancing performance: ● no feedback from faster layers ▼ regulation level feedback ▲ imbalances feedback and ■ imbalances and regulation feedback.



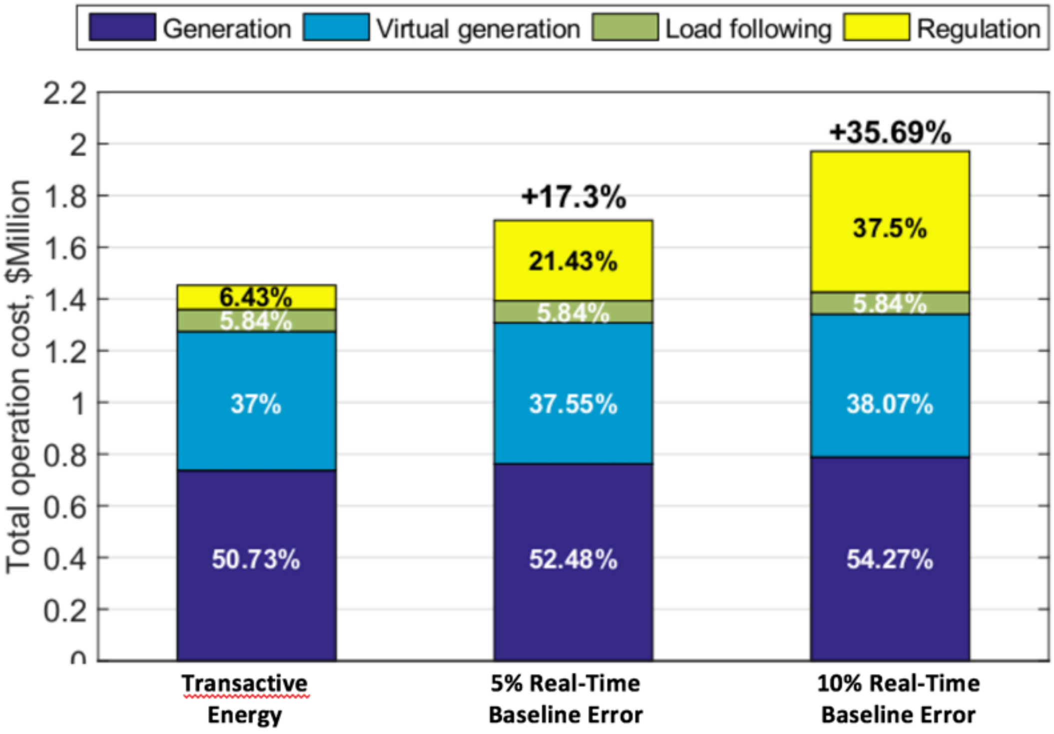
Second, as VERs are increasingly integrated into the grid, they motivate the need for an expanded set of essential grid services. Perhaps, the most prominent of these is the provision of different types of operating reserves that respond to grid conditions from as fast as several seconds – in the case or regulation reserves to up to thirty minutes in the case of secondary contingency reserves. Contingency (or emergency event) reserves have long been an essential grid service to cover the unscheduled outage of the system's largest source or generator. Similarly, regulation reserves are procured as a grid service to enable automatic generation control that maintains interchange schedule and frequency. Beyond these traditional grid services, variable energy resources require operating reserves during normal operating conditions; or simply normal operating reserves. Because VERs are inherently intermittent and uncertain, they affect the variability and the forecast error of the "net load" (i.e. total power demanded minus variable generation). Both intra-hour and inter-hour variability, when coupled with forecast errors, tend to cause power system imbalances. Consequently, recent research has shown numerically that as the net load variability and forecast error increases, the required quantities of load-following, ramping, and ramping reserves must also increase. Indeed, in the ISO New England study, the increasing penetration of VERs were shown in some cases to entirely exhaust all three types of operating reserves and that such a condition was closely tied to the presence of power system imbalances. Furthermore, the development of EPECS simulation models has provided the theoretical insight to develop *closed-form analytical solutions* for the quantities of all three types of operating reserves based upon the statistical properties of the net-load and the two energy market time steps.

VERs decrease the ability of existing system operations to balance the grid, and consequently increase the dependence on the available operating reserves. As the grid comes to increasingly rely on these resources, it is likely that the provision of grid inertia and voltage regulation will become important grid services as well. All of these new and increasingly important grid services will need to be thoroughly assessed; both for their physical impacts on grid reliability and for the economic implications of their procurement and provision.

At present, the electricity grid can accommodate relatively modest levels of VERs. However, as VERs gain penetration in the energy mix, the generation fleet slowly loses its dispatchability. In such a case, fast-ramping natural gas and hydro-electric power plants take on a prominent grid balancing role. At even higher VER penetration, the natural gas plants become "crowded-out" and dispatchable DSRs become the only remaining option for grid balancing. Such a scenario constitutes a fundamental transformation in the grid's architecture. At a technical level, DSRs take on a greater fraction of the control inputs for grid balancing, line congestion management, and voltage control. At an economic level, the market structures that incentivize these demand-side resources remain an open area of research.

For example, a recent EPECS study contrasted the techno-economic benefits of demand-side management using a transactive energy scheme vs the virtual power plant scheme in Order 745 of the Federal Energy Regulatory Commission (FERC). FERC is the United States federal agency that regulates the transmission and wholesale sale of electricity and natural gas in interstate commerce and regulates the transportation of oil by pipeline in interstate commerce. FERC Order 745 concerns demand response compensation in organized wholesale energy markets and implements demand response resources using "virtual power plants" that are incentivized downwards from their predicted demand baselines. As shown in Figure 4, the research concludes that the presence of demand baseline errors – present only in the FERC Order 745 implementation – leads to a cascade of additional system imbalances and costs as compared to the transactive energy model. A baseline error introduced in the day-ahead market increases production costs not just in the day-ahead market, but also introduces a greater net load error residual in the real-time market causing additional costs and imbalances. These imbalances, if left unmitigated degrade system reliability, or otherwise require costly regulating reserves to achieve the same reliability. An additional baseline error introduced in the real-time market further compounds this cascading effect with additional costs in the real-time market, amplifies downstream imbalances and further requires regulation capacity for its mitigation. Such works demonstrate how simulation can be used to evaluate the implications of new techno-economic electricity policy options.

Figure 4: A Comparison of the Total Production Costs from a.) the Transactive Energy Model b.) an industrial model with 5% demand baseline error and c.) an industrial model with 10% demand baseline error. The presence of a demand baseline only exists in the FERC demand response implementation.



Finally, the transformation of the grid's architecture brings about new stakeholders and jurisdictional challenges. Distributed generation transforms electricity end-users into new market prosumers who must ultimately be accommodated within an evolving economic and regulatory structure. Additionally, these new players span the various layers of the electric grid's jurisdictions; whether they are residential, microgrid, local or regional. A majority of these newly empowered stakeholders will emerge in the distribution system as the grid periphery is increasingly activated. The role and business model of electric utilities in this larger and continually evolving electric power enterprise control remain an open question.

Ultimately, as the electric grid's transformation takes hold of the future role of the utility, and the emergence of distribution system operators, and aggregators in new and often untested designs, there is a need to organize and validate these architectural alternatives in terms of a single analytical framework. An enterprise control approach allows for the simultaneous assessment of transmission and distribution systems, takes into account the changing nature of generation and demand, facilitates a greater understanding of the dynamic control properties of the electricity grid, and helps define the interdependent roles and relationships between new and old grid stakeholders. Advanced computational capabilities make such analyses increasingly tractable through simulation.

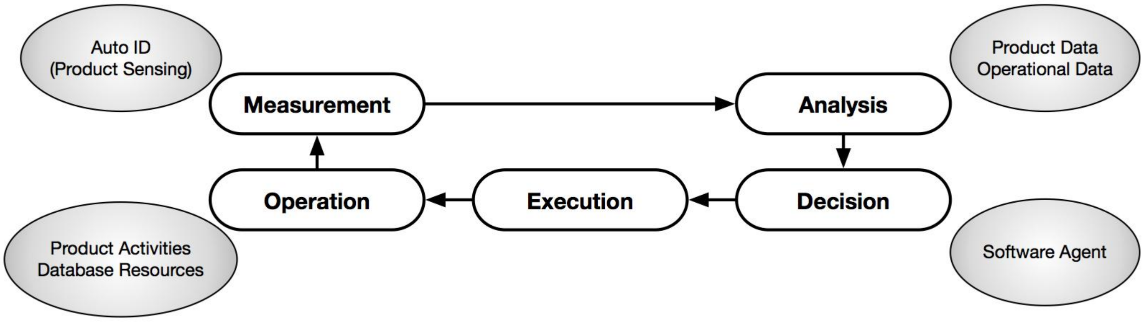
III. Energy Internet of Things

A. What is the energy Internet of Things?

The energy Internet of Things (eIoT) is one application of the Internet of Things (IoT). It is a technology that has expanded the use of communication technologies over the Internet, from user-to-user interaction to device-to-device interaction. As a way to connect humans, computers and devices, IoT presents itself as a key enabling technology of new energy-management approaches.

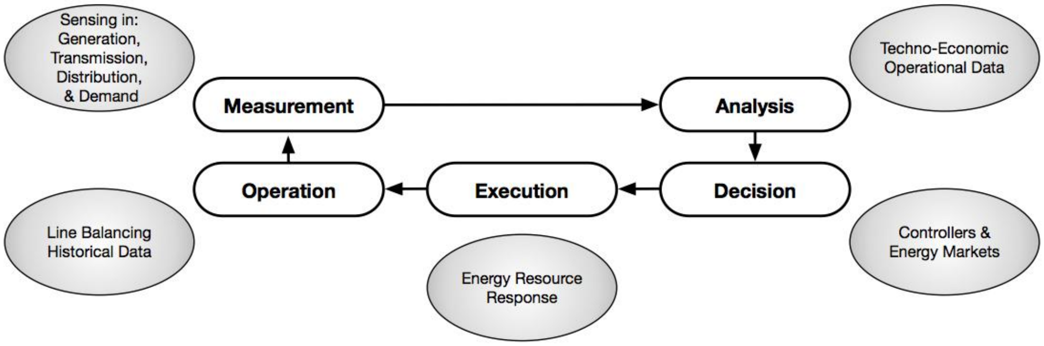
Perhaps the main reason why eIoT is so important is that the IoT vision, from its very conception, was meant to enhance supply-chain management solutions (as shown in Fig. 5) with intelligence in edge-devices (e.g. machines, material-handlers, and products). In such an architectural transformation, each "thing" would have device-level internet-enabled sensors that would serve to create its informatic counterpart on the internet. As IoT proliferated through supply chains, it would provide unprecedented visibility of supply-chain operations. Each piece of raw material, work in progress, or final product could be tracked in near real-time. When this information is relayed to enterprise (control) information systems, it could be used to support reactive and proactive decision-making on how to best manage supply chains. Indeed, many of the leading Industry 4.0 concepts rely on the Internet of Things paradigm.

Figure 5: A Closed Loop Control Framework "Industry 4.0" Production Systems Enabled by IOT



When the concept of IoT-based supply-chain management is applied to ``energy things'', it creates an eIoT-enabled control loop. As shown in Fig. 6, network-enabled sensing devices take measurements of the states and outputs of the physical system. The information is analyzed and used to make decisions independently or in coordination with other devices. Finally, decisions are sent to network-enabled actuators for implementation. Note that while some of the data is analyzed in real-time, a majority of the data can be used in predictive analytics to help understand the system and make decisions that affect the grid over longer time horizons.

Figure 6: A Closed-Loop Framework for Electrical Power System Management enabled by eIoT



In effect, the adoption of the energy Internet of Things represents a transformation of grid architecture in its own right. Whereas enterprise control simulation was discussed in the previous section as an analytical solution, eIoT is a technological solution that in many ways constitutes an architectural transformation. First, the tens of millions of physical devices at the grid periphery gain new informatic interfaces that did not previously exist. Second, such “smart” devices often gain new embedded control functionality. Third, the eIoT-enabled control loops (as shown in Fig. 3) may be organized into decentralized, distributed, hierarchical and centralized control structures. The choice of such an eIoT-enabled control structure places theoretical and practical limitations on the degree to which these “energy things” can be orchestrated into demand side grid services. Finally, transactive energy is the realization of a control loop interacting with market information, two-way communication networks, and real-time pricing mechanisms that incentivizes the generation and consumption of electricity. The ability to connect devices, create market signals, and influence generation and consumer behavior within an overarching energy-management framework is the essence of eIoT.

B. In what ways is eIoT transforming the grid's architecture?

Activating the grid periphery to provide essential grid services, however, is not a simple task. At the most basic level, the development of eIoT serves to advance grid-wide interoperability and ensure successful data integration schemes across the grid. As the need to monitor the two-way flow of information and power grows, so does the does the need for data gathering. Collected data must then be formatted, organized, and analyzed so to make informed predictions and decisions. Furthermore, as the diversity of devices grows, so does the diversity of the collected data. The development of the energy Internet of Things creates the granular monitoring environment necessary to transition the electricity grid from one that reacts to the shape of the load to one that can shape it and improve system operations.

Beyond the informatic integration of communication networks, activating the grid periphery is also difficult given its radial tree-like structure. The grid periphery contains millions or even billions of small interacting devices that must be coordinated and controlled so as to achieve higher-level functions. These devices and the data they produce must be integrated into the grid through a consistent economic and regulatory framework. This integration requires clear foresight by system operators and regulators while maintaining the reliability and security of the grid. Traditionally, the distribution system and hence, the grid periphery have not been actively controlled. Consequently, there exists much opportunity to better serve grid stakeholders through new and advanced energy management solutions. In some ways, utilities are well-placed to meet these new challenges. They can undertake the role of distribution system operators (DSOs) to manage not just the supply of electricity but also implement competitive retail electricity markets. Ultimately, the coordinated control of the eIoT-enabled grid periphery requires not only new technology but also grid operators and planners that can ensure its physical reliability and economic efficiency.

The energy Internet of Things is transforming the grid's architecture at multiple levels of the grid periphery. At the most granular level, devices and appliances with newly integrated control functionality are proliferating throughout homes, businesses and industrial sites. They also have the potential to transform the grid's architecture through microgrids and their associated energy management systems. Beyond their islanding capability, customer-owned microgrids can act as "curtailment service providers" or "demand-side aggregators" and participate directly in wholesale electricity-market demand- response schemes. Such participation motivates the development of transactive energy applications within the microgrid and implemented as eIoT control loops. Here, transactive energy is a means of advancing demand response initiatives while securing the operational needs of the grid's stakeholders. Through the use of smart devices connected in local area networks, consumers are exposed to a larger marketplace where energy "products" and grid services can be exchanged.

Within transactive energy applications, consumers and prosumers have the opportunity to exploit and benefit from changing real-time electricity market prices. Instead of procuring electricity directly from a utility, consumers can implement energy arbitrage schemes within transactive energy markets and maximize their benefits. Such arbitrage schemes can be implemented when consumers have access to the right eIoT devices, pricing information for wholesale and retail electricity markets, and transactive energy platforms that can coordinate power flows in response to this pricing information. Furthermore, the emergence of blockchain, as a distributed and virtual ledger, has advanced the likelihood that transactive energy applications will communicate transaction information securely. Transactive energy platforms effectively open up the demand-side to a wide range of applications, and as a result, have the potential to change incumbent business models in the distribution system. Naturally, the needs of residential, commercial and industrial consumers vary, and transactive energy management solutions have to develop accordingly. Therefore, it remains unclear how transactive energy applications will take shape or how utilities will adjust to the highly activated grid periphery.

IV. Modeling Interdependent Infrastructure Systems with Hetero-functional Graphs

A. Why do we need hetero-functional graphs?

Many “things” in the energy Internet of Things have a dual identity. They don’t just consume power, but also provide a service to a consumer. For example, the main purpose of a water treatment facility is to extract and treat water and deliver it via a network of pumps and pipes to the community. This example shows that many “energy things” at the grid periphery have functions outside the grid that drive electricity consumption patterns within the grid. Consequently, we must differentiate between purely “electrical things”, and “energy things” with multiple functions in multiple infrastructures.

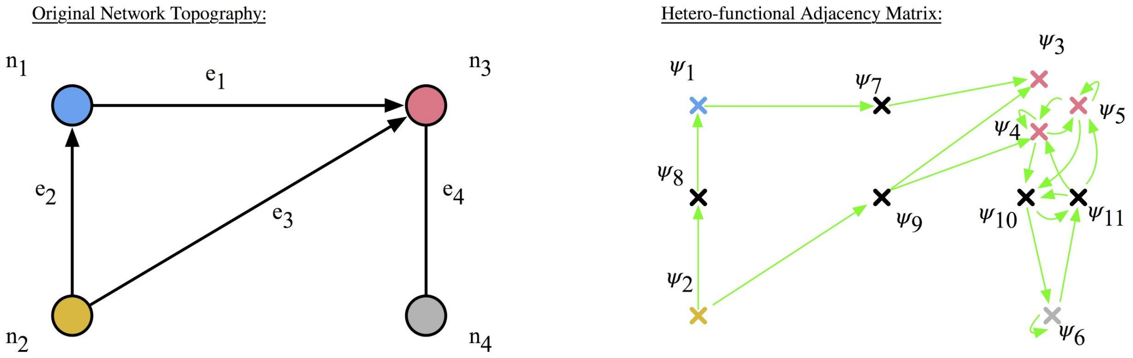
The integration of eIoT devices at the grid periphery introduces interdependencies between the power grid and other infrastructure systems. Consequently, decisions in other infrastructure systems could influence the operations of the power grid, and vice-versa. What was once the conventional task of controlling the power grid exclusively based upon observations in the demand has become the much more complex task of managing trade-offs between multiple infrastructures. Therefore, there is a need to develop models that integrate multiple infrastructures to support decision-making and control between them. However, methodological tools for the design of interdependent systems are required. Some work has used graph theoretic approaches while neglecting the intrinsic heterogeneity in these systems. Others have used graphical Model-Based Systems Engineering (MBSE) techniques that do not immediately lend themselves to quantitative analysis. For example, SysML activity and block diagrams are able to describe systems with arbitrary heterogeneity. To address the limitations of both approaches, hetero-functional graphs have been developed over the last decade, and most recently applied to interdependent smart city infrastructure.

B. What are Hetero-functional Graphs?

Hetero-functional graphs are a type of graph or network that explicitly describes the heterogeneity of function that is found in many networked systems including interdependent infrastructure systems. In essence, they provide a new ontological basis or vocabulary to model heterogeneous engineering systems. On the one hand, it draws concepts from Model-Based Systems Engineering to address the heterogeneity of interdependent infrastructure systems, on the other, it draws its quantitative nature from the formal mathematics of graph theory.

The left side of Figure 5 shows a small network representing a multi-infrastructure system. The four nodes represent a water treatment facility, a solar PV array, a house, and a parking lot at a work location. These nodes are connected by power lines, a water pipeline, and a road. The nodes of the graph presented on the left are not differentiated mathematically on the basis of the functions of the four resources in the system. In contrast, hetero-functional graphs differentiate themselves itself from conventional graphs, as they introduce a new ontology. More specifically, the nodes and edges of the graph are no longer physical resources. Instead, the nodes of the hetero-functional graph (denoted by ψ_1-ψ_{11}) are system capabilities, and the directed edges represent their sequential couplings (i.e. that the input of one capability follow the output of another).

Figure 5: Traditional vs Hetero-functional Graph Representation of a Small Network.



Legend:

Nodes:
n_1: Water Treatment Facility
n_2: Solar PV
n_3: House
n_4: Work Location

Edges:
e_1: Water Pipeline
e_2: Power Line 1
e_3: Power Line 2
e_4: Road

Degrees of Freedom:
ψ_1: treat water at water treatment facility
ψ_2: generate electricity at solar PV
ψ_3: consume water at house
ψ_4: charge EV at house
ψ_5: park EV at house
ψ_6: park EV at work location
ψ_7: transport water from water treatment facility to house with water pipeline
ψ_8: transport power from solar PV to water treatment facility with power line 1
ψ_9: transport power from solar PV to house with power line 2
ψ_{10}: discharge EV from house to work location with road
ψ_{11}: discharge EV from work location to house with road

Here, the system capabilities are defined as the mapping of a system function onto system form. This creates a new framework. For example, instead of being represented as a single node, the house is now represented by three capabilities (shown as capabilities ψ_3, ψ_4, and ψ_5 above). Similarly, the edges of the traditional network – on the left of Figure 5 -- (e.g. the power line from the solar array to the house) are also represented as capabilities. The physical resource "power line" transports power from the solar array to the house. Node ψ_9, therefore, represents the capability "power line transports power from the solar array to the house".

The system's capabilities are then coupled sequentially to describe how operands can move through the system. All of the feasible ordered pairs of capabilities (e.g. ψ_1,ψ_7) can be organized into a hetero-functional graph or network. This sequential coupling of coupling adheres to physical continuity laws and to the reference architecture of the system. For example, two capabilities precede the capability (ψ_3) "house consumes water". First, water needs to be transported from the water treatment facility to the house with capability ψ_7. Second, electric power needs to be transported from the solar array to the house with capability ψ_9.

In traditional graphs, edges may be either directed one-way or undirected two-way. This difference is accounted for in hetero-functional graphs with one or two transportation capabilities respectively. The undirected graph edge performs two functions; transport from house to work location, *and* transport from work location to house.

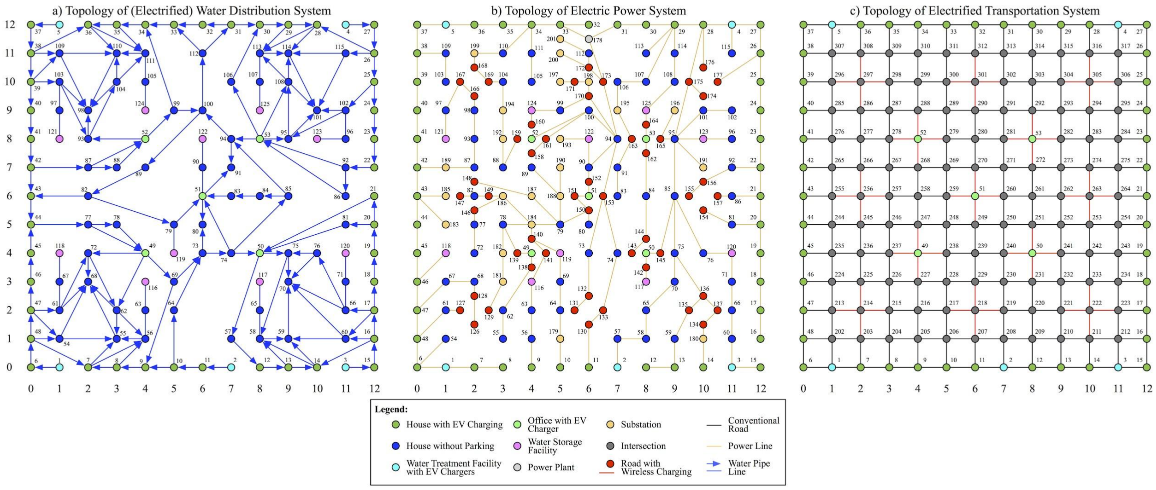
The simple example above serves to demonstrate the ability of hetero-functional graphs to explicitly model and differentiate between functions in the system. While traditional graphs use an ontological basis (or modeling vocabulary) of just nodes and edges, hetero-funtional graphs use one that identifies resources, functions, their mapping to form capabilities, and sequences of capabilities. This new ontological basis is of particular importance to the transformation of the electric grid's architecture. Now, as eIoT devices are integrated at the grid periphery to serve functions in multiple infrastructures, their hetero-functionality can be explicitly and quantitatively modeled. Consequently, and for the first time, the transformation of the grid's architecture can be informed by quantitative hetero-functional graph measures.

In addition to this purely static structural view, hetero-functional graph theory has been used to describe the dynamics of many largescale systems including electric power systems. In brief, hetero-functional graphs are used as an intermediate step in the derivation of well-established power systems engineering models like the power flow analysis model and the transient stability model.

C. Applications of Hetero-functional Graphs

Hetero-functional graphs have been used to study the structure and dynamics of a wide variety of complex engineering systems. They specifically lend themselves to the analysis of life-cycle properties such as resilience, and centrality in large, heterogeneous networks. Whereas Figure 5 shows a very small system, Figure 6 shows a much more complex example of an interdependent smart city infrastructure test case called "Trimetrica". This test case combines three infrastructure services: deliver potable water, electric power, and transportation. The study of resilience in interdependent networks of engineering systems investigates the feasible paths of service through the hetero-functional graph. Unlike paths in a traditional graph, service paths explicitly consider the feasibility of capabilities as one follows another in an engineering system.

Figure 6: Trimetrica, an interdependent smart city infrastructure test case that delivers services for potable water, electric power, and transportation.



Hetero-functional graphs have also been used to model dynamic systems in multiple domains. For example, work on industrial energy management has shown that a production system schedule can be manipulated to shift the load profile in an electric power grid. When this behavior is managed in concert with distributed renewable energy resources in a microgrid, it can be used to reduce carbon emissions and match electric demand with the weather forecast. Hetero-functional graphs have also been used to develop a hybrid dynamic model of an electrified transportation system. The model includes the microscopic hybrid behavior of traffic operations so as to study the kinematic and electric state of each EV in time. In the meantime, the model includes a continuous time model of the electric power system so as to manage balancing operations, line congestion, and voltage stability. In short, hetero-functional graph theory has demonstrated its applicability to a wide variety of interdependent infrastructure system domains. These domains are of direct relevance to the transformation of the electric grid's architecture as it integrates eIoT devices at the grid periphery.

V. Summary

This article has emphasized that the fundamental assumptions underlying the electric power grid's architecture are very much in a state of flux. The rising demand for electricity, the emergence of distributed renewable energy resources, the emergence of electrified transportation, the deregulation of power markets, and innovations in smart grid technology are all drivers that will cause the transformation of the grid's architecture. This work has advocated for enterprise control, the energy Internet of Things, and hetero-functional graph theory as technical solutions. Enterprise control recognizes that much of the transformation of the grid's architecture will be in the many layers of market operations and control that manage the grid's physical flows of power. Consequently, these layers must be simultaneously and holistically simulated to achieve techno-economic synergies. The energy Internet of Things recognizes that much of the transformation of the grid's architecture will be at the grid periphery where network-enabled devices will be orchestrated to provide coordinated energy products and grid services. Finally, hetero-functional graph theory recognizes that much of the transformation of the grid's architecture will require trade-offs with interdependent infrastructures of fundamentally different function. These three technical solutions taken together can help bring about and facilitate this transformation.

For further reading

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Biographies

Steffi Muhanji is a doctoral research assistant at the Laboratory for Intelligent Integrated Networks of Engineering Systems (LIINES) at the Thayer School of Engineering at Dartmouth.

Wester Schoonenberg is a doctoral research assistant at the Laboratory for Intelligent Integrated Networks of Engineering Systems (LIINES) at the Thayer School of Engineering at Dartmouth.

Amro M. Farid is an associate professor of engineering at the Thayer School of Engineering at Dartmouth, an adjunct associate professor of computer science at Dartmouth College and is the director of the Laboratory for Intelligent Integrated Networks of Engineering Systems (LIINES).