Structured Energy: Microgrids and Autonomous Transactive Operation

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***Abstract*-- We formally describe a topology of microgrids, including nesting, union, and intersection. By applying both market techniques and electrical switching we increase the value of autonomous microgrids by factoring operations management into microgrid management and cross-microgrid management, reducing the complexity of each, and simplifying architecture and resilience. We call this Structured Energy.**

In the evolving world of energy interoperation standards, interactions must be supported to, from, and within microgrids. We exploit standard interoperation technology to simplify issues of management, operations, complexity, reliability, and marketability of distributed generation and energy resources.

Structured energy is a key step toward management of scarcity and of surplus. Local balancing of supply and demand, and presenting a more manageable load to the outside, can be much more effective in a structured energy world.

Examples apply Structured Energy to a mixed-use industrial and commercial development, assembly of microgrids, energy surety in underdeveloped areas, and fault resilience.

***Index Terms*—Power grids, Smart grids, Emergent phenomena, Topology, Supply and demand, Microeconomics, Autonomous agents, Power system management, Environmental economics, Transactive energy**

I. NOMENCLATURE

We use the following terms in this paper:

Topological Space
Microgrid
Consumption-Only Microgrid
Supply-Only Microgrid
Transactive Energy
Transactive Operation
Micromarket
Structured Energy
Aggregating and disaggregating microgrids

II. INTRODUCTION

THIS paper addresses the architectural capabilities and functions to aggregate,[1] disaggregate, design, and evolve collections of microgrids [1]. We use a broad definition of microgrid, and show how to arbitrarily combine and split or partition microgrids, and discuss how to use and adapt such understanding to real-world examples.

From the business perspective, microgrids balance supply and demand both internally and (when not separated or islanded) between external and internal actors. The community served by a microgrid intends to achieve specific local goals, such as reliability, carbon emission reduction, diversification of energy sources, and cost reduction. To these ends, these communities self-manage the local generation, distribution, storage, recycling, conversion, and internal flow of electricity to consumers

From the architectural perspective, a microgrid is a group of devices with self-management, and optionally storage, generation, and consumption of energy. A microgrid is also an aggregation of one or more microgrids that provides energy switching, transportation, and management across its constituent microgrids. This creates a hierarchical structure where the edges are from a microgrid to its constituent microgrids. Microgrids are a key concept for Structured Energy [2] [3] and Collaborative Energy [4].

The operational autonomy of microgrids allows a *divide and conquer* [5] approach to managing, consuming, and supplying energy, and application of Service-Oriented Architecture (SOA) [6] techniques to achieve scalability and independent evolution for implementations.

We will show how our approach supports recursive composition and decomposition of microgrids into respectively larger and smaller microgrids.

Transactive Operation is a particular approach to Transactive Energy [7] that addresses real economic interaction rather than applying control by using fiat prices disconnected from reality [8].

The specific approach we use applies micromarkets [9] [10] and therefore supports Transactive Operation. Other means of operation management are possible but provide less evolutionary capability and are more complex.

III. MANAGED ENERGY AND COLLABORATIVE ENERGY

Managed and Collaborative Energy were first defined in a keynote talk [4] at the initial NIST Smart Grid Workshop. We

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[1] We use *aggregate* and *disaggregate* as synonyms for *compose* and *decompose* in the sense of to assemble from component parts or to disassemble into a [potentially different] set of component parts.

distinguish between *Managed Energy* where the goal is to manage end nodes to better fulfill grid-side goals, and *Collaborative Energy* where the grid and business actors make choices consistent with their business goals. Collaborative Energy is characterized in part by asking, not telling, the connected nodes for information and behavior changes.

This notion is key to more recent work such as transactive energy (See e.g. [7] and the semantics of price [8]).

IV. MICROGRIDS FOR STRUCTURING

A. Why Microgrids?

We consider Microgrids as defined by the Galvin Initiative [1]:

- "[Microgrids] achieve specific local goals, such as reliability, carbon emission reduction, diversification of energy sources, and cost reduction, established by the community being served."
- "[S]mart microgrids generate, distribute, and regulate the flow of electricity to consumers, but do so locally."

Microgrid operations must maintain a balance of supply and demand. Markets are used to balance supply and demand in a broader sense; by extending microgrid operations to encompass market interactions we combine two sets of largely compatible goals.

Microgrids are self-managed, with management addressing local conditions of supply and demand, and satisfying local rather than more global needs.

A microgrid can operate as a part of a larger grid or can operate independently of the larger grid. A stand-alone microgrid never connects to a larger grid. We consider autonomous microgrids, whether attached to a larger grid or not. Because autonomous microgrids operate themselves and hide their internal characteristics from external markets, microgrids are a natural fit with service orientation.

B. Supply, Consumption, and Energy Flows

Commonly we think of microgrids that balance their own internal supply and demand. Before we address the net flows into and out of a given microgrid we describe several common cases that stretch the boundaries of what is considered a microgrid:

- Consumption-only microgrids
- Supply-only microgrids

Consumption-only microgrids have been the most common—a typical energy managed commercial building is an example. It must work to manage and limit demand in coordination with supply contracts that may involve expensive demand ratchet charges.

A supply-only microgrid might provide redundant supply devices to allow greater robustness of exported energy. An increasingly common technique combines supply with some microgrid-managed energy storage to better manage outputs. This trend is exemplified by combining energy storage batteries, hydrogen generation, or other storage with wind turbines to provide more controlled output. [11] [12].

We lump supply and demand, flows in and out of a microgrid together into a Net Flow.[2] The net flows of energy into a microgrid measure over time what is needed to balance after internal management has been applied.

A well-behaved microgrid provides value by smoothing, regulating, and optimizing flows using its own business needs and goals, not that of the energy delivery grid [13].

We note specifically that a consumption-only microgrid provides value in a better-regulated, smoother load, simplifying cross-microgrid energy transfers in which it participates.

V. A TOPOLOGY OF MICROGRIDS

A. Introduction

We want to aggregate and disaggregate microgrids, and study was of performing that aggregation and disaggregation. (See e.g. [14] and Section VII Structured Energy Techniques)

To support those goals, we demonstrate that microgrids form a topology, so that the union, intersection, and complement of a microgrid (within a containing microgrid) are also microgrids.

B. What Is a Topology?

Topology is a mathematical discipline that studies (among other things) invariant properties of objects under transformations; the term *topology* is also applied to a structure of open sets on a base set. Adapting [15] as quoted in [16]:

"A **topological space** is [then] a set G together with a collection of subsets of G, called open sets and satisfying the following axioms:

(1) The empty set and G itself are open.

(2) Any union of open sets is open.

(3) The intersection of any finite number of open sets is open. The collection τ of open sets is then also called **a topology** on G."

We will show that the collection of microgrids within a grid forms a topology, and apply that knowledge in later sections.

C. Microgrids and Topologies

First we define a set G, which we will call the *enclosing microgrid*, then a topology on G.

Let G be the set of all energy-producing or consuming devices within a given energy grid. By definition the energy grid permits communication and elements may delivery and/or accept delivery of energy from others.

First, we define the open sets to include the microgrids contained in G together with the empty set:

$$\begin{aligned}\tau = \{ &\mathit{all\ sets\ of\ members\ of\ } G \mid \mathit{members\ can} \\ &\mathit{communicate\ and\ deliver\ or\ accept} \\ &\mathit{delivery\ of\ energy}\} \cup \emptyset\end{aligned}$$

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[2] While there may be economic value in separately accounting for the flows, as in separate versus net metering for generation and consumption, our analysis needs only net flows.

In the context of an energy grid G, the condition is true for the grid G itself. The empty set is explicitly a member. Axiom 1 is satisfied: G and the empty set are members of τ.

The demonstration for Axiom 3 is simpler, so we consider that next. We must show that any finite intersection of members of τ is also in τ.

Since the members of G by definition can communicate and deliver or accept energy from each other as members of G, any set comprised of members of G may as well. So Axiom 3 is satisfied. Moreover, each member of G that participates in the intersection also has communication and energy delivery/acceptance.

For Axiom 2 we must show that any union of members of τ is itself a member of τ.

Since the number of devices within G is bounded, the cardinality of G is bounded by the cardinality of the power set of its elements. This reduces the problem to showing that the axiom applies to any finite union, and the proof to a finite induction.

Consider members $MicroGrid\ A$ and $MicroGrid\ B$. As they are both members of τ they individually satisfy the constraint on energy delivery and acceptance. Now consider a member, say MicroGrid C, that contains both A and B. First, $MicroGrid\ C \subseteq MicroGrid\ G$, so two elements within $MicroGrid\ A \cup MicroGrid\ B$ by assumption can communicate and supply/deliver energy between them. Therefore Axiom 2 is satisfied.

Therefore the microgrids contained in a grid G form a topology.

D. *Additional Issues*

We are interested in containment, intersection, and union of microgrids; our functional definition of a microgrid is in fact the same as that for the containing grid (and G itself is a microgrid). So we can use the term grid and microgrid interchangeably; where we wish to emphasis aggregation or disaggregation will we commonly use the term microgrid.

Note that we give an existence proof, not an engineering description—to be cost-effective one would likely create structures with gateways rather than effectively full crossbar switchgear. In a later section we will describe how to achieve what is effectively point-to-point energy exchange.

We have two issues yet to address: How do we effectively and efficiently implement the energy delivery and acceptance that's assumed by our definition? And how do we manage the operational balancing across joined or within intersected microgrids?

VI. FLOW ANALYSIS AND ENERGY EXCHANGE

A. *Delivery of Energy*

We introduced net flows into and out of a given microgrid in Section IV. B. . In this section we show how to accomplish energy delivery from microgrid A to microgrid B when they are not necessarily directly connected.

The technique is similar to the induction proof that microgrids form a topology in Section V.

Delivery from A to B can be accomplished

(a) Directly if there is a direct connection between A and B
(b) Indirectly through some containing microgrid's delivery mechanisms
(c) Indirectly by (e.g.) economic substitution

All are, of course, constrained by relevant energy transfer limitations.

Case (a): In our example A and B are adjoining electrically, and can transfer energy through existing connections.

Case (b): We rely on the existence of one of the containing microgrid, say microgrid C, that manages energy flows between its elements, in particular between A and B, who can transfer energy through C's connections.

Case (c): A common source delivers energy to A and B within some containing microgrid. To effect delivery from A to B, A lowers its inflow, B increases its inflow, and A compensates B for any differential costs. The outflow case is similar.

The common source may be found by searching up the tree of containing micromarkets. Economic substitution encompasses a wider range of assets, i.e., thermal energy from solar panels and thermal energy from grid-based pre-consumption are more-or-less direct economic substitutes [9] [17].

B. *Operational Balancing for Microgrids*

Again we assume that each constituent microgrid balances supply and demand within itself. We have two cases to examine: Given microgrids A and B, it suffices to describe how to manage operations

(a) Across the union of A and B ($A \cup B$) and
(b) Within the intersection of A and B ($A \cap B$)

For (a) we establish a micromarket where elements of A and B participate. In the alternative A and B participate and address the net flows (looking inside their respective microgrids and to the market for their pairwise combination to manage transfers).

For (b) we establish a micromarket for elements in which both A and B participate. If A and B use micromarkets for balance (and transactive operation) then we can configure them (rather than recode them) to participate.[3]

So for each operation on members of the topology τ we have shown how to deliver energy and how to balance supply and demand across the microgrid created by intersecting or composing an arbitrary number of other elements of τ.

VII. STRUCTURED ENERGY TECHNIQUES

A. *Recursive Aggregation*

Aggregation (or composition) of microgrids is performed by union operations in the topology. Consider the chain of operations performed to get to the outermost (micro)grid: that chain defines a tree with the root of a sub-tree being the aggregated microgrid and the leaves being the microgrids that

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[3] This is MarketContext in Energy Interoperation's service definitions [18].

were aggregated.

We call this recursive aggregation—there are no *a priori* limits on the depth of the aggregation tree.

B. Recursive Disaggregation

Similarly, disaggregation (or decomposition) of microgrids is performed by intersection operations in the topology. We may also think of this as sub-setting or factoring of the disaggregated microgrid.

This likewise establishes a tree with the root of a sub-tree being the decomposed microgrid and the leaves the parts.

There are some obvious constraints (described in [14]) on covering the set of elements, but at any given time we must keep in mind that not all possible combinations make economic, engineering, or mathematical sense.

VIII. IMPLEMENTING AGGREGATION/DISAGGREGATION

The actors that define the business logic and encapsulate business requirements for each element need to participate in markets, energy management, and other interactions.

These interactions should

(a) Be service-oriented
(b) Be consistent across the elements
(c) Not constrain the internal implementation of the elements
(d) Be as simple as possible
(e) Support transactive (market) interactions and price / product definition communication
(f) Communicate projections of consumption and supply
(g) Be open, freely usable, and support open source implementations
(h) Be standards-based

In the evolving world of energy interoperation standards, interactions must be supported to, from, and within microgrids. This is clearly required for aggregating and disaggregating microgrids with our approach.

OASIS Energy Interoperation [18] is a completed and fully open standard for market interactions, and fully meets the requirements above. In particular, Energy Interoperation is free to read, use, and apply, making it an ideal choice.

The specification standardizes and evolves the architecture of OpenADR 1 [19], and is the basis for the OpenADR2 profiles [20], including their profile enabling communication from Independent System Operators to Aggregators to Facilities to Devices [21] [8] [22].

All of those actors and others supported with the same interaction patterns, code, and message, may involve interaction inside, outside, and to, from, and between microgrids.

For failure resilience a structured microgrid and micromarkets can adapt with only configuration changes, and without coding at the nodes.

IX. PLANNING FOR SCARCITY AND SURPLUS

As Metcalfe [23] has pointed out, planning for scarcity is the path to needed eventual abundance of energy. Management of scarcity is a crucial role of the producers and consumers of energy.

Local balancing of supply and demand, and presenting a more manageable load to the outside, can be much more effective in a structured energy world.

Planning for scarcity with energy management and transactive operation also enables dealing with surplus. Economic choices are not single-ended; a price- or cost-responsive microgrid can deal with both scarcity and surplus.

X. APPLYING STRUCTURED ENERGY

We conclude with a brief description of four applications of structured energy.

A. Mixed Industrial and Commercial Microgrid

See Figure 1. Consider a mixed microgrid C, with an industrial portion A that is a net exporter of energy, and a commercial portion B that is a net consumer of energy. (The use of various alternative and distributed energy resources is not relevant at this level of detail—they reduce the net inflows and increase the management complexity).

One might think of this as one microgrid inside another. But applying structured energy decomposition, we see rather that there are at least three microgrids: The containing microgrid (C), the industrial microgrid (A), and the commercial microgrid (B) formed by subtracting A from C, or alternately by aggregating A and B to form C.

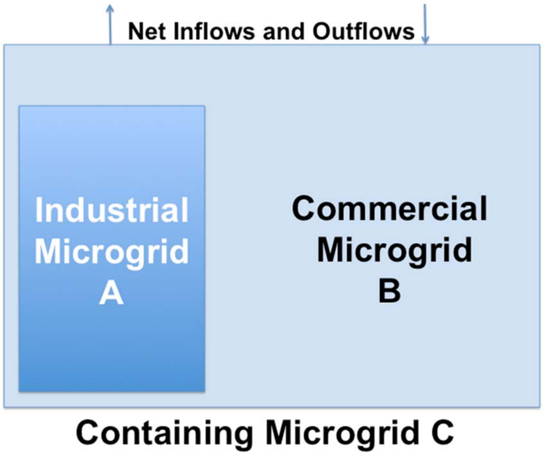

Figure 1 Three Microgrids

The issue is not how we got to this state, but in what useful ways we may look at the present state.

Transfers may not be easy, and the net energy needs of B are key to fulfilling the business goals of the businesses in microgrid B. Islanding of A from the broader grid would likely cause greater management challenges and shortages in B than in A which has generation sufficient for itself and some surplus.

B. Top-Down Evolution of Microgrids

We've seen an example of top-down evolution already: as microgrid C was developed, the specific needs of the industrial area may have led to the creation of microgrid A, and B is the remainder with respect to C.

Over time, other needs will arise, and additional generation might be sited and managed by microgrid B. Or perhaps A would be disaggregated or decomposed into its supply aspects and consumption aspects. In either case, the terminology of structured energy gives us a way to describe the evolution and hints on how to effectively engineer and implement the evolution.

C. Bottom-Up Evolution of Microgrids

Consider an underdeveloped populated area with limited and unreliable electrical and other energy supplies. Consumption may include industrial, commercial, and residential.

By securing a microgrid containing some supply and some consumption, increased energy surety can be brought to that microgrid service area.

Separate areas, say surrounding supply resources can similarly stabilize and improve energy surety by forming a microgrid, and taking into account local needs and conditions.

When connections are available or have been designed and deployed, these multiple microgrids may compose into a larger microgrid, which may also supply energy to territories at their borders.

Over time the composed (and containing) microgrid can adapt and extend by composing neighboring microgrids, which it has already helped stabilize through energy exports and imports.

The populated, industrialized area thus realizes greater energy surety over time, while expanding the area managed, and creating by aggregation a microgrid that can be decomposed into smaller parts should the need arise.

D. Resilience of Microgrids

Microgrids provide greater energy surety, one kind of resilience. Within a microgrid we can apply structured energy techniques to dynamically configure the aggregation hierarchies, adapting to failure of supply or consumption.

Using the standards described in Section VIII. The adaption for resilience is accomplished by reconfiguration of the referenced micromarkets and Actors.

Aggregation and disaggregation can be applied dynamically, contributing to resilience in the face of failure of components, interconnects, and entire sub-microgrids.

XI. CONCLUSIONS

We have defined structured energy, and demonstrated that microgrids form a topology.

We have shown high-level interoperation standards that can manage the union, intersection, aggregation, and disaggregation of microgrids over time and as a vocabulary for structuring collections of microgrids.

We’ve shown how microgrids can evolve over time and demonstrate several applications of structured energy via top-down and bottom-up aggregation and disaggregation.

Aggregation and disaggregation can be applied dynamically, contributing to resilience in the face of failure of components, interconnects, and entire sub-microgrids.

Structured energy, using microgrids as the basic components, thus allows planning for scarcity, ensuring long-term plenty, and taking advantage of surplus when available.

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XIII. BIOGRAPHIES

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He has developed enterprise product architectures for Bell Labs, Unix System Labs, Novell, and BEA, and has done related standards work in OASIS, ebXML, the Java Community Process, Object Management Group, IEC, and the IEEE.

He earned a Ph.D. and M.S. in Computer Sciences (minor in Electrical and Computer Engineering) from the University of Wisconsin-Madison.

Toby Considine is recognized thought leader in applying IT to energy, physical security, and emergency response. He is a frequent conference speaker and provides advice to companies and consortia on new business models and integration strategies.

Toby has been integrating building systems and business processes for longer than he cares to confess. He has supported and managed interfaces to and between buildings, cogeneration plants, substations, chilled water plants, and steam and electrical distribution. This work led to Toby's focus on standards-based enterprise interaction with the engineered systems in buildings, and to his work in the Organization for the Advancement of Structured Information Standards (OASIS).

Toby is chair of the OASIS oBIX Technical Committee, a web services standard for interface between building systems and e-business, and of the OASIS WS-Calendar Technical Committee. He is a former co-Chair of the OASIS Technical Advisory Board.

Toby has been part of national smart grid activities since delivering the plenary report on business and policy at the DOE GridWise Constitutional Convention in 2005. He is a member of the SGIP Smart Grid Architecture Committee, and is active in several of the NIST Smart Grid Domain Expert Workgroups.

Before coming to UNC, Mr. Considine developed enterprise systems for technology companies, apparel companies, manufacturing plants, architectural firms, and media companies old and new. Before that, Toby worked in pharmaceutical research following undergraduate work in developmental neuropharmacology at UNC.