BLOCK-LEVEL MICROGRIDS FOR POWER SYSTEM RESILIENCE: SCALING AND IMPACTS

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ABSTRACT

This paper presents a new approach for the coordination and scaling of microgrids, known as EcoBlocks, and discusses the ability of EcoBlocks to function as electrical islands in an adaptive manner. We analyse the impacts of EcoBlock design elements such as block size, energy management strategies, and DC power distribution on grid resilience, flexibility and efficiency under large-scale deployment. By enabling new operating schemes including routine grid support as well as adaptive islanding during major disturbance events, EcoBlocks could significantly enhance the beneficial role of microgrids for grid resilience.

INTRODUCTION

If deployed at large scale, embedded microgrids—aggregations of generation (often renewable), energy storage, loads, and intelligent energy management, which can optionally disconnect from the main grid—are a potential revolution in resilience, flexibility, and sustainability of electric power systems. Embedded microgrids offer value for resilience through adaptive islanding, the ability to smoothly and intentionally transition back and forth between grid-connected mode and operating as a power island. Benefits include more reliable electric service for microgrid residents, pockets of service to help society cope with wide-area outages, reduced risk of cascading failures (via smart automated decisions about when to disconnect or provide grid support) and facilitating recovery [1-3]. Furthermore, by dynamically managing local energy resources while still connected to the main grid, microgrids can control their net power to optimize efficiency, minimize cost, or maintain stability [4].

The most straightforward locations for microgrid deployment are large single customers with natural separation points from the grid, such as campuses. However, to enable adaptive islanding at large scale, we must address the question of how to segment an existing medium-voltage power distribution system into a collection of microgrids. Answering this question requires an integrated system design approach that addresses size, installed infrastructure, and operation of the microgrids, as well as a scalable framework for their interactions with the main grid, particularly the distribution operator. The approach must be compatible with today's planning and operational conventions, while also anticipating and resolving the challenges that may arise under high microgrid penetration levels.

This paper discusses a new concept for the design, coordination and scaling of urban microgrids, known as EcoBlocks, and draws from a pilot project to establish an EcoBlock in Oakland, California, led by the University of California, Berkeley's Renewable & Appropriate Energy Laboratory [5]. The EcoBlock project aims to transform city blocks into sustainable microgrids through home energy retrofits, installation of solar photovoltaic (PV) and energy storage systems, and smart energy and water management. The EcoBlock model also emphasizes sharing of resources, including electric vehicles (EVs), energy storage and water reclamation systems. By aggregating customers into local resource communities, EcoBlocks address not only technical but also legal, economic and institutional challenges of multi-customer microgrids.

To guide the design of EcoBlocks, we have surveyed the spectrum of possible impacts they could have on power system operation, with particular attention to dependence on scale or penetration level of EcoBlock deployment. We then identify system design aspects with great potential for positive impact. First, we discuss how a collection of EcoBlocks could represent a large and geographically diverse resource for flexibility services and optimal power flow, using their ability to adjust net power in response to grid operator signals. Second, in a stochastic modeling exercise, we show that the block scale is an advantageous intermediate level of aggregation between individual homes and entire distribution feeders. EcoBlocks are large enough to ensure high self-sufficiency due to statistical load aggregation, but small enough for efficient coordination of resources. Third, the choice of DC infrastructure can improve efficiency and facilitate adaptive islanding. While each of these design elements may be shared with other microgrid and local energy community concepts, we hypothesize that the EcoBlock's unique combination of features and whole-systems retrofitting approach will be especially transformative.

DESIGN ELEMENTS AND IMPACTS

Control of net power

There is concern that increased deployment of distributed energy resources such as PV and EVs, if not coordinated, will have adverse effects on the grid such as voltage violations and volatility, reverse power flow, and overloading of utility equipment [6]. In microgrids, however, these resources are aggregated into a single unit along with energy storage, controls and monitoring. Therefore, if managed appropriately, microgrids such as EcoBlocks should be able not only to avoid these adverse impacts, but also to contribute additional services to enhance grid flexibility and efficiency. For example, controlling the energy storage to flatten the net power profile could benefit the grid by reducing voltage variability, peak loading, and losses [7]. Reduced variability and loading, in turn, could reduce wear on legacy voltage regulation equipment and delay infrastructure upgrades. Collections of EcoBlocks could also be actively recruited by distribution and/or transmission system operators to perform flexibility services such as voltage support, power balancing, or frequency regulation. Large-scale deployment of these microgrids would increase both the size of this flexibility resource and the diversity of geographic locations in which it is available. Unlike virtual power plants, EcoBlocks would have the capability to observe and prioritize local constraints such as distribution feeder voltage while providing grid-level services.

The aggregation of resources in an EcoBlock, combined with sensing and communication infrastructure, could also mitigate the uncertainty typically associated with variable generation and improve situational awareness for distribution operators. However, with increased penetration level of EcoBlocks comes increased risk of overwhelming the grid operator with excessive information, necessitating new software platforms to distill a limited number of actionable messages from the wealth of data [8]. There must also be a scalable approach for the grid operator to determine and signal how the EcoBlocks should behave. With simple time-of-use pricing and a large number of controllable resources, there is a risk of overcompensating for problems (for example, many resources injecting power in response to high prices could turn a supply shortage into an excess) [7]. Large-scale microgrid deployment therefore needs a management strategy with higher granularity with respect to time and location.

Intentional islanding at the block scale

For a portion of a power system to island, it needs sufficient generation and storage resources for both dynamic power balancing and longer-term energy balancing. These resources must also be controlled intelligently, along with load shedding when needed, to maintain island stability, prioritize critical loads, and resynchronize with the grid [1, 3]. The scale of the unit participating in adaptive islanding—including physical size, number of customers, and electrical connectivity—affects both self-sufficiency and ease of management. In this section, we analyze the dependence of these two criteria on the unit size, from individual household to block to distribution feeder.

Self-sufficiency analysis

Aggregating 10 or more homes into a microgrid has been shown to improve self-sufficiency by reducing net-load variability [9-10]. Here, we apply the probabilistic self-sufficiency assessment method of [9] to evaluate more systematically the relationship between the number of customers in a power island and its self-sufficiency. In this method, we determine the self-sufficiency of a power island during a particular islanding event by calculating the amount of energy stored and delivered to loads at each time step during the event, given time-series generation and load data and energy storage system characteristics. We perform these calculations for simulated islanding events starting on each day of the year, and record the total demand during each event and the amount of that demand that could be met. Then, we divide the sum of load served during all these events by the sum of demand during all the events, to compute our self-sufficiency metric, the year-averaged fraction of load served (FLS). The data set, from the Pecan Street, Inc. Dataport [11], contains hourly generation and load data from over 100 homes with PV in Austin, TX, USA. For each island size under consideration, these homes are randomly allocated into groups of that size. The load and generation time series for each home in the group are added to produce aggregated generation and load time series for the entire group. Then, the year-averaged FLS is computed for each group, creating a distribution of FLS for each island size. This process is repeated 50 times, and the final result is the average of the 50 distributions.

Results of this stochastic simulation process are shown in Figure 1. In Figure 1a, the energy storage capacity in each simulated island is sized to supply the island's average power demand for 8 hours. The storage system power rating is assumed to correspond to a full charge or discharge in 4 hours (i.e., twice the average load in this case), and efficiency and self-discharge corresponding to Amber Kinetics' flywheel [12]. The ratio of yearly PV generation to yearly energy demand at each home ranges from 0.19 to 1.42, with an average of 0.65. For these simulations, islanding events are assumed to start at midnight, with the energy storage 50% charged, and last for 24 hours. While the exact FLS values vary when the starting conditions and durations differ, the general trends are consistent.

Figure 1a shows that the average fraction of load served increases slightly when multiple homes are aggregated, from 0.58 for individual homes to 0.61, 0.62, and 0.63 for groups of 2, 3, and 5 respectively. This increase is explained by the non-coincident peaks in households' net load, which can surpass the rated power of an individual home's energy storage system, but are less significant on the scale of multiple homes' aggregate load and storage. While the change in the mean is relatively small, and the rate of improvement nearly negligible for groups larger than 5, the variance of self-

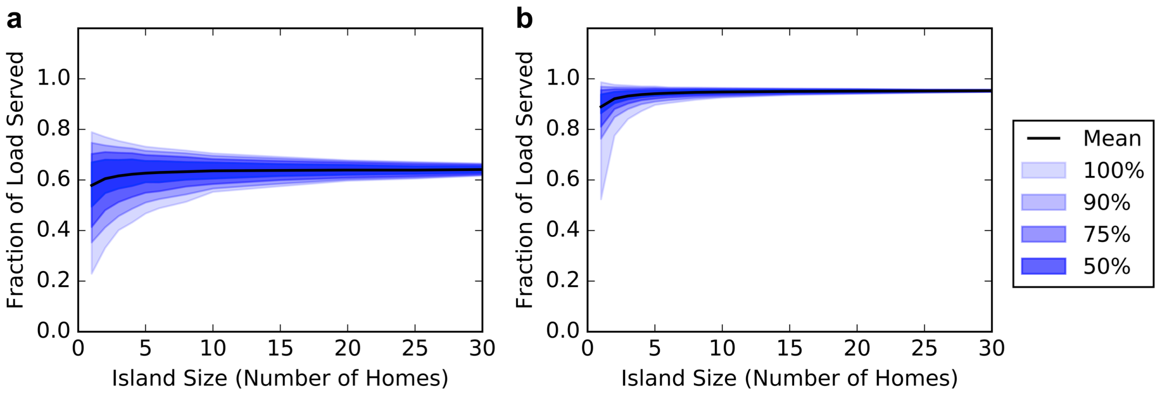

Figure 1. Dependence of the year-averaged fraction of load served in a power island on the number of homes in the island. The mean and spread of the FLS are computed using 50 independent groupings of homes. The ratios of yearly generation to yearly load and energy storage capacity to average load are (a) 0.65 and 8 hours and (b) 1.3 and 16 hours.

sufficiency shows a greater dependence on island size. For example, the year-averaged FLS ranges from 0.23 to 0.79 for individual homes, 0.47 to 0.73 for groups of 5, and 0.57 to 0.69 for groups of 15. The high variance with small group size results from the differing PV system sizes and load curves among the homes; homes with the smallest PV systems tend to exhibit the lowest self-sufficiency. Then, when many homes with differing PV system sizes are aggregated into a microgrid, the overall self-sufficiency approaches the mean. The significance of this result is that in the independent home case, if the homes have similar amounts of critical load, but differing limits on PV capacity, e.g. due to roof space and geometry, then some will have excess energy to power noncritical loads while others will struggle to meet even their critical energy needs. The shared electrical infrastructure of a microgrid, on the other hand, would help to ensure equitable distribution of energy among the residents and ease the selective disconnection of noncritical loads.

The self-sufficiency can be improved by installing a greater amount of energy storage or PV generation. Specifically, doubling the energy storage size and doubling the PV generation in the simulated islands each independently increase the mean FLS by about 15 percentage points. Figure 1b shows the self-sufficiency results after scaling both PV generation and energy storage by a factor of two (i.e. with yearly generation equal to 1.3 times demand, and energy storage capacity able to supply average load for 16 hours). These design choices improve self-sufficiency in both the average case and the worst case for groups of all sizes—but even though the self-sufficiency of individual homes is increased, improvement is still seen when several are aggregated into a microgrid.

Distribution grid partitioning for adaptive islanding

Since the statistical aggregation benefits apply to islands with a few customers or more, there are multiple ways a grid could be partitioned into islands with high self-sufficiency. Perhaps the most intuitive unit for adaptive islanding is the distribution feeder, as it is easily separable from the rest of the grid through a circuit breaker at the substation. A key problem with the feeder scale, however, is that it encompasses a relatively large number of customers (hundreds or even thousands), making it difficult to coordinate generation and voluntary load curtailment. Assigning liability for power quality issues also becomes more challenging with a greater number of players.

In a city block, by contrast, the smaller number of customers and smaller geographic size should facilitate both automated energy management and coordination of customer behavior. Blocks also offer a convenient physical location for shared resources—such as the communal energy storage system, water management system, and EV charging stations that characterize the EcoBlock—and are small enough for these systems to be integrated and retrofitted simultaneously. Customers may be more willing to accept a resource sharing model when the resources are located near their residence and shared with a small community of neighbors. Finally, particularly in lower population density areas, distribution feeders rely on overhead conductors that are susceptible to damage from weather and vegetation. If these lines become damaged, a collection of independent block-scale microgrids (especially with underground internal power distribution) could continue to be energized, while a single feeder-level power island could not. In sum, the city block is an advantageous scale for adaptive islanding, being simultaneously large enough to ensure high self-sufficiency due to statistical aggregation and small enough to facilitate internal coordination of resources.

DC power distribution

A third notable aspect of the EcoBlock concept is a DC power distribution system. Although challenges remain for DC microgrids—protection is more difficult than for AC due to larger fault currents and lack of a zero crossing, and the majority of commercially available appliances today expect AC—a number of advantages exist. For one, PV generators produce DC power, and many modern loads and energy storage devices rely on DC power internally as well [13-14]. The preliminary EcoBlock design therefore incorporates DC circuits connecting the PV arrays to the storage system and the storage system to DC loads such as lighting, EV chargers, and some appliances. This configuration avoids unnecessary AC-DC conversion steps and associated energy losses between these components.

DC microgrids are also expected to facilitate adaptive islanding. Since they do not require frequency regulation or reactive power balancing, maintaining stability in islanded mode is more straightforward compared to AC microgrids [13-14]. DC microgrids could even connect to each other via DC links to form larger power islands, enabling larger-scale sharing of energy resources during extreme events. Furthermore, synchronization of phase angle and frequency before connection to each other or the main grid becomes unnecessary, reducing the risks and complexity of post-event recovery [13]. An inverter will act as the point of common coupling between the EcoBlock's DC circuit and the main grid, providing a safe and convenient transfer mechanism for islanding operations. EcoBlock residents will have the option to use additional small inverters to supply their remaining AC loads from the islandable DC circuit.

CONCLUSIONS AND FUTURE WORK

While the final electrical design of the EcoBlock may evolve due to site-specific factors and product availability, the most fundamental design aspects—control of net power, islanding capability, block scale, and DC power distribution—make the EcoBlock a potential agent of transformation for power system resilience, flexibility and efficiency. The precise value of EcoBlocks will depend on the characteristics of the particular distribution system to which they are connected. For example, we expect adaptive islanding to be most beneficial for feeders with low redundancy (radial configuration) and high likelihood of extreme weather, and voltage support to be of most value on long feeders with greatest risk of voltage problems. Therefore, future work will investigate the types of feeders for which EcoBlocks offer the most significant benefits for efficiency, resilience, and economy.

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