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Regulatory islanding parameters in battery based solar PV for electricity system resiliency

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Abstract-- **Distributed battery based solar power photovoltaic (PV) systems have the potential to supply electricity during grid outages resulting from extreme weather or other emergency situations. As such, distributed PV can significantly increase the resiliency of the electricity system. In order to take advantage of this capability, however, the PV systems must be designed with regulatory parameters in mind and combined with other technologies, such as smart energy storage and auxiliary generation. Strengthening policy and regulatory support could encourage deployment of PV systems designed for resiliency and improve public safety to power during emergencies. This paper specifies the goals of power resiliency and explains the reasons that most distributed PV systems as installed today in the United States are technically incapable of providing consumer power during a grid outage. It presents the basics and regulatory parameters of designing distributed PV systems for resiliency, including the use of energy storage and Microgrids. The paper concludes with critical policy and regulatory considerations for encouraging the use of these distributed system designs.**

Index Terms-- **Distributed power generation; Photovoltaic systems; Microgrids; Auxiliary transmitters; islanding detection.**

I. Nomenclature

Microgrid: is an electrical system that includes multiple loads and distributed energy resources that can be operated in parallel with the broader utility grid or as an electrical island.

Islanding and islanding detection: islanding is a condition in which a battery storage based grid continues to power a location even when electricity from the electric utility is no longer present. Anti-islanding is when the production of powers stops in case of disruptions and switch energy storage mode. The common example of islanding is a grid supply line that has solar panels attached to a battery.

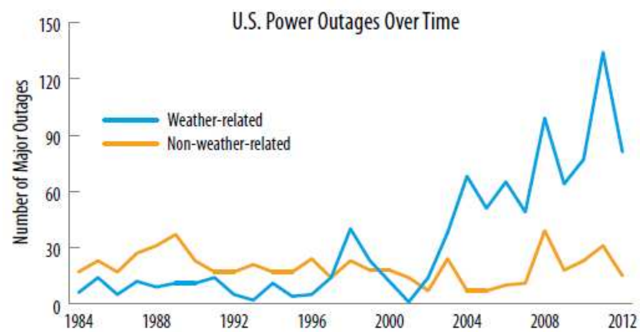
II. Introduction

THE electricity system resiliency Focuses on prevention of power disruption, protection of life, and property dependent on electricity service. Mitigation to limit the consequences of a power disruption impacts the time and resources needed to restore service electricity supply. As shown in Fig. 1, the number of weather-related power disruptions has grown significantly within the past decade.

Severe weather is now the leading cause of power outages in the United States [1]. Sustained weather-related outages impact daily life, health and safety support services, communities, and the economy, with inflation-adjusted cost estimates of $18 billion to $70 billion per year, on average [2].

Fig. 1. Major weather-related power outages; those affecting ≥50,000 customers increased dramatically in the 2000s [4].

Electricity losses associated with Hurricane Sandy (2012)



are estimated to have resulted in $27 billion to $52 billion in economic losses from lost wages, spoiled inventory, grid damages, and other sources. According to the Edison Electric Institute, the economic impact of blackouts caused by natural disasters can be significantly higher than the cost of system repairs [3].

Electric utilities and local, state, and federal governments understand the urgency for prompt electric system restoration, but are often constrained by limited resources during emergencies. Increasing the grid's resiliency can reduce the time and resources needed to supply power to critical facilities; such as hospitals, shelters, and wastewater treatment facilities, and restore the entire system to normal operations [4].

III. Designing PV Systems to Provide Energy Resiliency

Deploying solar PV technology in conjunction with energy storage, in combination with auxiliary generating sources, or within a Microgrid allows solar energy to contribute to the resiliency by providing localize power when the grid is down. The roles of these supporting technologies and applications are covered below.

A. Electricity Storage

Given the variable nature of renewable energy resources, including solar, energy storage is a necessary component of a distributed PV system to provide reliable power during a grid outage. Batteries are the most commonly used and well-suited storage technology for small, distributed solar PV applications, although other types of storage may be available for utility-scale systems.

Batteries are integrated with solar PV panels through the inverter. The inverter must be able to automatically select between charging the batteries, providing electricity to the on-site load, and/or feeding electricity onto the grid. The function that is selected at any moment depends on electricity demand from the on-site load, the grid status, battery status, and the available solar resource. When the grid goes down, the inverter must isolate the PV system from the grid, while continuing to supply the on-site load with electricity from the solar panels and/or storage unit. The system must also be capable of isolating all local loads from the grid, to avoid creating a grid fault.

To date, the major barrier to the deployment of energy storage devices in conjunction with PV systems has been cost [6].

Fig. 2. Battery price projections [7].

But battery prices have declined notably in recent years. One study indicates that the incremental cost of adding batteries to a residential PV system in California declined at an average rate of 11% per year between 2007 and 2013 [5], and costs are expected to continue dropping (see Fig. 2). Based on analysis by Rocky Mountain Institute, PV systems with storage will be cost-competitive with grid power in some locations within this decade [7].

Another means of making storage more economical for the PV system owner is to compensate owners for the benefits that storage provides to the broader electricity system and to society. Storage may add value through the provision of:

- Ancillary services to the grid, such as voltage control,
- Demand-side management to smooth peaks in the load on the utility system,
- Improved power quality (e.g., batteries can smooth the variable output of a PV system),
- Electricity to critical facilities during major power outages
- An increased ability to integrate high levels of distributed generation onto the electricity system

When PV system owners can realize these values, either through market mechanisms or through government incentives, the cost-effectiveness of storage improves. Even with today's battery prices, if storage owners receive payments for services, such as frequency regulation, a PV system with storage could more than offset the added cost of the batteries. The potential to avoid losses that can result from power outages is another incentive to invest in storage (see Case Studies A, B and E, the examples of Midtown Community School and Princeton University, Appendix) [8]-[9].

B. Community Energy Storage (CES)

CES brings together many of the benefits of customer-owned storage with those of utility-scale ownership and operation, and is receiving increasing attention in relation to distributed solar generation [10]-[11]. CES is different from storage associated with individual distributed energy systems, because a CES unit serves all customers connected to a particular distribution area [12]; similar to the backup capabilities of customer-owned storage, CES units can isolate one portion of the distribution system and provide service to an entire feeder during an outage on the broader grid. The units can be sized from several kilowatts of capacity up to several megawatts, and may offer economies of scale over customer-owned storage. CES is generally thought of as a utility-owned and operated storage model, although community-owned feeder level storage units are conceivable. Utility ownership of community-level storage allows utilities to provide potentially greater reliability benefits to all utility customers, integrate the cost of storage into the utility rate-base, and ease the integration of higher levels of distributed generation.

Considerations for regulators wanting to encourage the development of CES include the establishment of standardized specifications for the storage systems and their interconnection with the utility system. American Electric Power (AEP), the utility that has thus far spear-headed the CES model, has published the open-source "Functional Specifications for CES", which outlines connection, control, communication and other proposed standards for the deployment of CES (AEP 2014). Other organizations, such as the National Institute of Standards and Technology and the IEEE are also working on clarifying standards for CES units [13].

C. Rate Structures Impact on the Use of Distributed Solar with Storage

The rate structure, retail prices, and compensation for PV generation can all influence the use and economics of storage. Solar PV system production coincides fairly well with daily utility system peak demand, when utility generation costs at the highest. Customers that are under a time-of-use (TOU) rate structure are incentivized to use their solar generation when prices for grid electricity are at the highest. In some cases, storage may prove economical if it better allows the customer to use stored solar energy when grid prices are at the highest. Customers that are subject to demand charges may find it economical to use storage for load shifting by charging batteries with solar and using that power to avoid triggering demand charges.

Under the typical residential net metering rate structure, there is little or no economic incentive for a PV system owner to divert power to a battery to be used later, unless reliability is a concern. So, in general, solar PV with associated storage encourages the use of grid power during off-peak hours, which could help to smooth the overall utility system load curve and reduce the need for peaking generation from centralized facilities.

With higher retail rates and lower compensation for PV generation, different behavior is encouraged. As interconnection policies and incentives for energy storage gain attention, it has become apparent that it is important to be able to distinguish whether an energy storage unit is being charged with electricity generated by a distributed solar system or with grid power. Energy arbitrage refers to the practice of storing electricity during periods with low energy prices and discharging it at periods with high energy prices. Customers with solar systems may install battery units with the intent of saving excess electricity from their solar system. But the same batteries could also be charged using electricity from the grid. This means that, in the absence of controls, electricity could be purchased from the grid, stored, and sold back to the grid for a higher price than it was purchased. Without metering controls, it is impossible to confirm whether the electricity being discharged from the battery originated from the grid or from the customer's solar panels. In California, this issue was addressed by requiring specific metering configurations to track the flow of electricity to and from the battery and solar system [14].

A related issue is with regards to whether a storage unit associated with a distributed solar system is eligible to receive incentives that are designed to encourage solar development, if the batteries are charged, to some degree, with grid-supplied power.

In 2015, the Internal Revenue Service confirmed that the cost of storage units connected to distributed PV systems is, indeed, eligible for the Federal Investment Tax Credit (ITC). However, customers must track what percentage of the electricity used to charge the battery comes from the grid over the first five years. Reductions in the tax credit apply when the percentage falls below a certain threshold, with no credit available if the percentage is below 75% [15].

D. Microgrids

A Microgrid is a combination of electricity generation, wires, communications and control technologies, and energy storage. It is able to operate either in a grid connected fashion or independently, in an island mode. Microgrids are fully customizable to specific end-user needs, and offer the opportunity for improved reliability, cost-efficiency, and environmental benefits [11].

In the past, Microgrids have been of interest primarily for military bases and remote communities, but the application of Microgrids is rapidly evolving. Cities, communities, and public institutions represent the next phase of Microgrid adopters, largely driven by resiliency concerns. Five U.S. states have passed laws or announced investment programs to establish Microgrids for reliability purposes. Critical facilities such as hospitals, wastewater treatment facilities, and schools are already targeted for Microgrid development, but this is likely to extend to privately owned services, such as gasoline fueling stations and grocery stores.

Distributed energy generation is increasingly part of new Microgrid development, particularly in cases in which reliability is a key concern. Incorporating distributed solar systems into Microgrids adds value to the Microgrid and allows additional value to be drawn from the solar system.

In some cases, improved integration of high levels of distributed renewable energy generation resources is a driver for the development of Microgrids. Energy storage and control technologies (key features of Microgrids) provide voltage control services that facilitate high levels of variable generating resources on a distribution network. And, on the other hand, Microgrids enable solar PV to provide reliability benefits through the provision of demand response and grid services. Barriers, most of which are regulatory in nature, inhibit Microgrid growth. Microgrids typically require the use of existing lines or the construction of new power lines within the defined zone, which may infringe on utility franchise rights. Microgrid operation may involve the exchange of power between parties or the transmission of power across streets or public areas, which could make operators subject to public utility regulation. The lack of clarity regarding interconnection rules and who pays for necessary equipment or network upgrades is another major barrier. Standards for interconnection procedures and costs would relieve these uncertainties and facilitate deployment. Finally, the facilitation of new financing models for developers of Microgrids would help overcome the barrier of high upfront costs and provide the option of Microgrids to a broader number of end users.

E. Regulatory and Policy Consideration

There are many reasons that existing distributed solar energy systems are not designed to provide resiliency and backup power when the grid is down. There are also numerous supporting technologies that allow distributed solar energy to play a role in resiliency, and the case studies in this paper (listed in the Appendix) provide examples of where solar has proven this ability [Case study C and D, Appendix].

Through an understanding of the value that solar energy brings to the table, the necessary supporting technologies, and the deployment barriers that still exist, regulators and policymakers can support the development of distributed PV to build a more resilient energy system.

The regulatory and policy considerations for supporting the use of distributed solar energy for increased resiliency are summarized in the bullets below:

- Create rate structures or incentive programs such that system owners can be compensated for the variety of benefits and services provided by energy storage associated with distributed solar energy.
- Support the development of distributed solar PV systems that can operate independent of the electrical grid in emergency situations, particularly at critical facilities.
- Clarify rate structures for owners of PV systems that are capable of being grid-interactive and standalone (hybrid).
- Clarify interconnection procedures for distributed PV systems with storage.
- Clarify rate structures and interconnection procedures for CES and associated distributed PV systems.
- Enable a variety of ownership structures and financing mechanisms for CES.
- Identify critical locations that would benefit from Microgrid development.
- Clarify interconnection procedures and utility upgrade costs related to Microgrids.
- Allow for third-party participation in the development of Microgrids that incorporate utility systems within that Microgrid.

IV. ISLANDING TEST CONDITIONS AND PROPOSED METHODOLOGY

Few researchers examined the sensitivity of different resilience parameters for battery based distributed Microgrids. A total of seven parameters were tested on the test frame for various islanding and non-islanding events [12]-[14]-[15], such as single phase faults, three phase fault, and load and capacitor switching cases at different power mismatches between generation and load demands according to the test parameters in Table I [15]. The magnitudes of these parameters used by other researchers (i.e. *dp/dv, dp/dq, dq/dp, dq/dv, dv/df…*) and *df/dq* (proposed in this paper) were compared after ignoring the initial transients.

The comparison showed that *df/dq* reflected a steady and reliable changes during the battery based islanding scenario.

However, if the behaviors of these parameters are compared with non-islanding events, it is very difficult to differentiate between islanding and non-islanding events, with the notable exception of *df/dq*. It is also observed that there are maximums and minimums of *df/dq* that can be used as thresholds for distinguishing islanding from non-islanding events. This will form the basis of the proposed parameter presented in this paper.

TABLE I
IEEE Test Frame Parameters [15]

IEEE TEST FRAME INDICES

Indices	Value	Indices	Value
Mini hydro rating	2 MVA	Voltage (L-L)	11 kV
Induction generator rating	0.05 MW	Resistance	42.46 Ω
Photovoltaic generation	1.00 MW	Capacitance	29.11 μF
Frequency	50 Hz	Inductance	0.348 H

It is determined from the five case studies standardized by IEEE 1547-2003 protocol (see Appendix); that the rate of change of frequency over utility power at peak hours (*df/dq*) is the most sensitive indicator for resiliency [10]. A new passive islanding detection technique that employs this parameter is subsequently proposed. The generalized methodology of the proposed passive technique is illustrated as follows. The proposed passive technique measures the absolute *df/dq* at peak hours cycles (case study A, B, and E listed in the Appendix). The proposed technique is initiated when:

$$(df/dq)\ measured > (df/dq)\ min > 1 \qquad (1)$$

Where, (*df/dq*) min is the minimum set point that avoids the unnecessary activation of the flow of power when utility is disconnected. If and only if Eq. (1) is satisfied, the process of determining the maximum magnitude of *df/dq* ((*df/dq*) measured) is activated. In this process, the initial conditions are neglected after the event starts to ensure that the data reached a certain degree of certainty. After this, *df/dq* measured is determined within a certain period of time, while islanding is detected when Eq. (2):

$$(df/dq)\ measured < (df/dq)\ max < 1 \quad (2)$$

Where, (*df/dq*) max is the threshold value to distinguish islanding from all other non-islanding events. Values for (*df/dq*) min and (*df/dq*) max are determined from the electric optimum calculator provided by the cases studies in section IV. In non-islanding cases, most of the values fall below that of unity. Hence, we set (*df/dq*) min to unity to avoid excessive activation, while (*df/dq*) max is set in such a way that will allow it to differentiate between the remaining non-islanding and islanding events. However, both of these values are specific to certain systems, and can be set accordingly. The flowchart of the proposed technique is shown in Fig. 3 [15].

V. Modeling of the Test System

To comparatively study different passive parameters and test the validity of the proposed islanding detection technique shown in Fig. 3, an existing 11 kV distribution found in the five case studies are considered. A standard test condition is applied to the five case studies shown in the Appendix in accordance to IEEE 1547-2003 protocol [14]. The grid system of each case study consists of a mini hydro (MH), an induction generator (IG), a photovoltaic generation (PV), utility grid, 33 buses and 29 lumped loads [16].

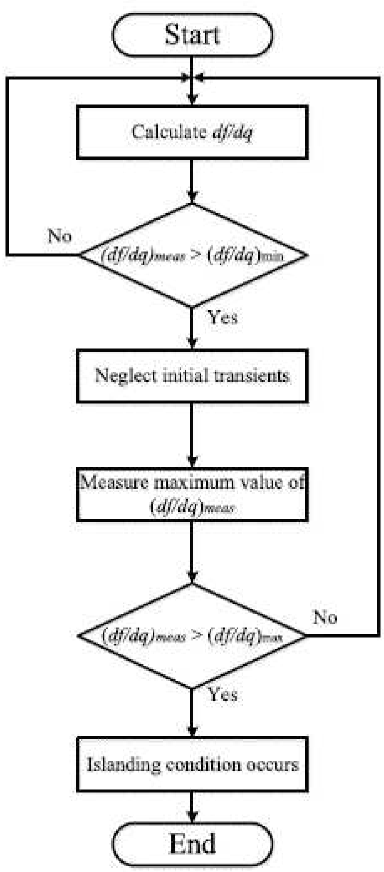


Fig. 3. Flow chart of proposed islanding detection technique [15].

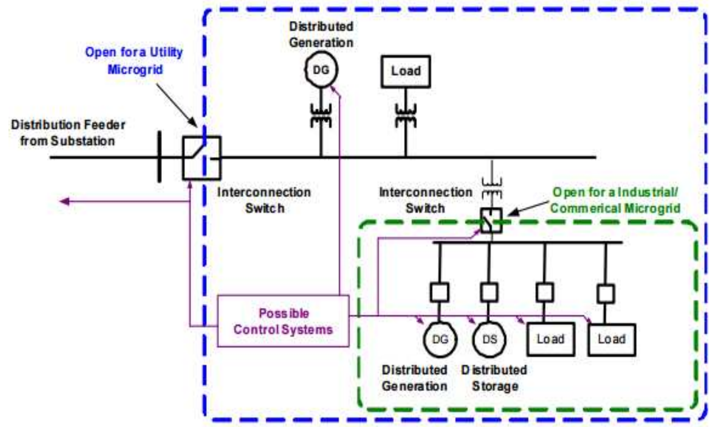


Fig. 4. IEEE 1547 standard test system [12].

VI. Discussion

In review of the 5 cases (Appendix); this paper critically identifies critical regulatory and resiliency design parameters that can be used in safety techniques to detect islanding and non-islanding events. It is observed that the rate of change of inverter frequency over utility power at peak hours (*df/dq*), which is referred to in this paper as "power generation mismatch" can effectively detect minute disturbances in power supply to the grid; which mean ($df/dq > 1$) will result in less resilience factor and unsafe to operate in emergency disruption of power; while ($df/dq < 1$) is considered safe and resilient.

The IEEE 1547-2003 protocol provides a standard test frame to verify the performance of the islanding detection techniques proposed in this paper. Hence, the 33-bus system used in all five case studies is modeled on the aforementioned test frame, as illustrated Fig. 4 [14].

The performance of the islanding detection scheme depends entirely on the nature of the load. Hence, the IEEE 1547 standard recommends selecting a parallel RLC load to validate the performance of an islanding detection technique, as it is more rigorous as opposed to other types of load. The IEEE 1547 test frame indices for the DERs and loads are presented in Table I [15].

VII. Conclusion

In conclusion, the power generation mismatch has an opposing effect on the variation of frequency and resiliency in real time environment. As a result of this, a new passive technique based on (*df/dq*) is proposed. The testing results indicate that the proposed technique is able to distinguish islanding from other events, such as load variation, and motor starting.

The new passive islanding detection technique proposed by the authors was based on the rate of change of frequency over utility power at peak hours for battery based systems. The performance of the proposed technique is verified and tested on the five case studies listed in the Appendix, and for many other various islanding and non-islanding cases [11]-[13]. The results confirm the ability of the proposed technique to distinguish islanding and non-islanding events for battery based systems. The proposed technique discerns islanding up to an accuracy mismatch of 0.05 KW, resulting in highly reliable accuracy, low cost, and zero impact on power quality, making it appropriate for real-world execution.

VIII. APPENDIX

The below five case studies selected from the literature represent a diversified prototype for modeling the test system parameters according to IEEE 1547 protocol. These case studies provided the basis to conduct relevant performance analysis of various parameters related to battery based PV solar systems as discussed in the previous sections.

A. Borrego Springs Microgrid Project

Borrego Springs Microgrid Demonstration Project "A" neighborhood in the city of Borrego Springs [15], in San Diego County, California is a working example of how distributed solar systems and CES can improve reliability. The town, which is in a relatively remote location, is supplied power via a single transmission line that is at risk for disruptions caused by weather-related events. The town is part of a Microgrid pilot project, funded by the U.S. Department of Energy, San Diego Gas and Electric, the California Energy Commission, and other partners to improve reliability of electricity supply. Members of the community installed a total of 700 kW of distributed rooftop solar capacity. CES units were added at the substation and distribution circuits, along with communication and control technologies. A handful of residents had invested in residential-sized battery storage, which was integrated into the system. Residents were also enlisted to participate in a price-driven load management program that used automated price signals sent to home area networks (HANs) to manage loads such as pool pumps, electric vehicles, and thermostats.

The distributed generation, storage units, and control technologies that make up the community's Microgrid have provided power during planned and weather-related outages, and successful islanding of neighborhood distribution circuits has been demonstrated on multiple occasions. Experience with the project to date indicates the potential to use the Microgrid to re-energize the distribution system after an outage; this capability would represent a new functionality of Microgrids and a significant contribution to resiliency [16]

B. Midtown Community School

Midtown Community School installs hybrid solar-diesel system with storage. Hurricane Sandy, which hit the east coast in 2012, disrupted electricity service to many cities for days or weeks before repairs could be made. Without electricity, emergency shelters often depend on diesel-powered backup generators to supply light and heat. Due to the size and impact of Hurricane Sandy, diesel fuel for backup generators and emergency vehicles was in desperately short supply, and floodwaters often made it difficult to get available fuel to where it was needed. In many cases, diesel generators were themselves covered in floodwaters.

Midtown Community School in Bayonne, New Jersey, however, had a constant supply of electricity throughout the event, thanks to its hybrid solar-diesel generating system, installed in 2004. The school served as a community shelter during Hurricane Sandy as a result of this system. The local school district had worked with Advanced Solar Products to develop a system that would allow the 272 kW of existing solar panels on the school to provide power during a grid outage. The inverter was modified and a diesel generator was added. The system was manually 'islanded' during Hurricane Sandy to provide electricity to the school when the broader grid was down. When the sun is shining, the diesel generators idle at low levels, resulting in a drastic reduction in fuel consumption and reserving valuable supplies [17].

C. T-Mobile

T-Mobile uses solar-hybrid systems to improve resiliency of communications. T-Mobile is installing solar PV to replace or augment its diesel emergency generators, reducing emissions and saving fuel costs while providing emergency backup for communications services. To test the viability of the switch to solar, the company replaced some diesel generators with solar systems for a 16-week trial. Results indicated significant potential savings in fuel costs, and T-Mobile now plans to extend the deployment of solar for backup power to its cell towers on a national scale. Even in cases in which a switch to solar is not practical, combining solar and diesel can increase the length of time diesel reserves last during an emergency, and free up limited fuel supplies for other uses. As the technology included in antennas and radios evolves, less power will be needed at each tower, increasing the viability of solar for these applications [16].

D. Microgrid for resiliency in Vermont

The country's first 100% solar-powered Microgrid is being constructed on a repurposed landfill to increase energy resiliency for the town of Rutland, Vermont. The community experiences frequent storm-related power outages and was one of the hardest hit areas of the state during Hurricane Sandy.

The innovative project includes 2.5 MW of solar capacity and 4 MW of battery storage, enough to supply 365 homes with electricity during normal weather conditions, or power the public shelter during emergency situations. Both lithium ion and lead acid battery technologies are included in the design in order to take advantage of the different cycling qualities of each. Green Mountain Power, the local electricity provider, is developing the project with support from the Department of Energy and other partners. The utility expects to gain valuable experience that it can apply in other locations of its territory. In addition to backup power, the project's storage capacity will provide additional value through quick-responding frequency regulation services for the grid [13]-[18].

E. Princeton University Microgrid

Princeton University has developed a Microgrid that includes a 5 MW backup diesel generator, 5.4 MW of solar PV capacity, chillers, and thermal energy storage, among other technologies. The university's goals in its development included cost reduction and emission reduction. Under normal circumstances, the Microgrid is connected to the broader utility system. The on-site generation is used to reduce the amount of electricity purchased during peak demand periods and avoid capacity charges. Frequency regulation services are sold into the regional transmission organization's (RTO) ancillary service market, which adds further economic benefit. The resiliency benefits of the Microgrid were proven, and brought the Microgrid into the public eye, after Hurricane Sandy. When disruptions were detected on the main grid during the storm, operators disconnected the Microgrid and successfully supplied critical power to the campus, providing services to students and avoiding millions of dollars of research-related losses [12].

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X. BIOGRAPHIES

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