Smart, Clean Neighborhood Grids:

Redesigning Our Electric System To Help Communities Power Through Blackouts

Executive Summary

A global electricity trend towards clean, resilient and renewable distributed power is underway. This trend is driven by the increased threat of climate change, increasingly old and costly utility infrastructure, and the advent of new software and hardware that enable an affordable, distributed energy future. As customers adopt energy saving and management solutions like rooftop solar and battery storage, this theoretical future is already coming to fruition. Yet in order to harness the full suite of benefits to individuals and society, we need advancements in power system planning, equipment and technologies, and operations.

Distributed, clean energy is an optimal solution to the growing challenges of transitioning towards a 100% renewable energy grid. As utilities look to harden existing centralized infrastructure and improve resilience by relying on outdated and polluting technology, our proposed concept demonstrates how clean, distributed energy resources can achieve a smarter, more resilient electricity system.

In one instance[1], California-based utility Pacific Gas & Electric has proposed reinforcing its substations with what amounts to utility-scale fossil fuel generators to mitigate the impact of Public Safety Power Shutoffs (PSPS). This paper shows that we can work together with the utility to deploy distributed energy resources (DERs), both at the distribution substation and along the neighborhood distribution network, to combat the challenges of an increasingly vulnerable grid and deliver a clean, resilient, solution.

We must coordinate resources to realize this vision. While the fundamental building blocks are already in place, it will require further research and technological advancements to become reality. We will also need to see a rapid increase in the adoption of distributed energy resources. Forward-looking policy that prioritizes consumers and community-based solutions will be critical to achieving this goal and advancing the necessary redesign of our electricity infrastructure.

[1] System Reliability RFO - Distributed Generation Microgrid Services Phase, PG&E. https://www.pge.com/en_US/for-our-business-partners/energy-supply/electric-rfo/wholesale-electric-power-procurement/system-reliability-rfo.page?WT.mc_id=Vanity_rfo-systemreliabilityrfo

Concept

We need better electricity architecture for three fundamental reasons:

First, the cost of fossil fuel-based electricity is rising while the cost of renewable technology is decreasing.

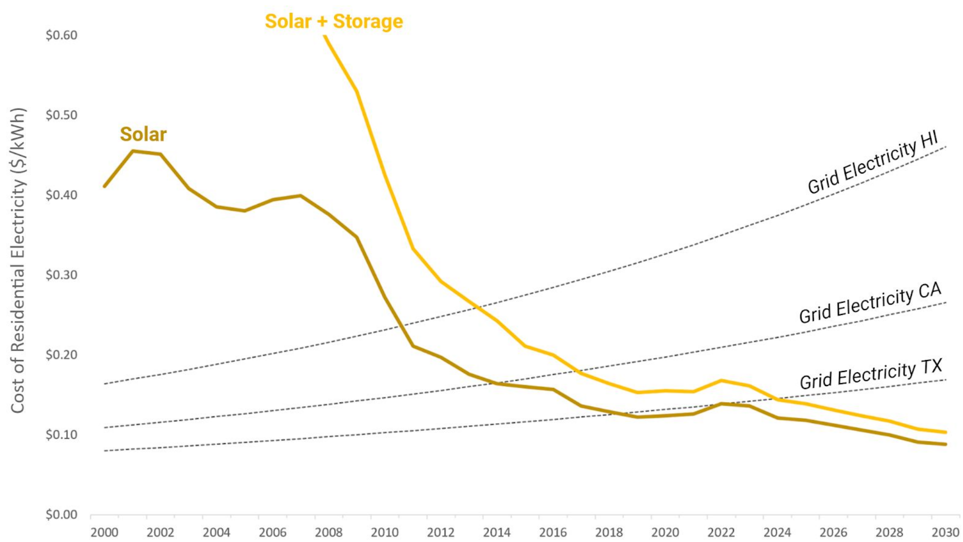

Exhibit 1: Actual and Predicted Cost of Solar & Storage Compared to Utility Rates[2]

Grid-tied rooftop solar and battery storage is already capable of forming its own nanogrid at the customer level. Within the next decade, it will likely be below the cost of grid-served power in most US markets, and therefore financially viable.

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[2] *Methodology: Rooftop solar modeled as 7 kW, storage modeled as 10 kWh. Historic $/kW solar prices from "Tracking the Sun 10", NREL, September 2017, for residential solar. Future $/kW solar prices from NREL Annual Technology Baseline 2017. Historic $/kWh storage costs from Bloomberg New Energy Finance Research Note March 23, 2016, Lithium Ion Battery Cost Breakdown and Forecast, estimating a battery pack cost of 2.27x battery cell cost. Future $/ kWh storage costs from Bloomberg New Energy Finance Lithium-ion Battery Costs and Market, July 5, 2017 (Sample Slides). Solar and storage costs levelized at a 6% weighted average cost of capital. Historic grid retail rates from EIA Form 826. Future grid costs extrapolated at CAGR of 2000-2015 cost increases.*

Second, there has been an increase in disasters caused by existing electrical infrastructure, especially in California.

The effect of fire-related property damage and fatalities over the last decade has increased drastically due to high voltage electricity running through dry, wind-prone areas. This costs billions of dollars annually, and has only one known practical solution with a low up-front cost: de-energizing utility transmission lines. However, de-energization is diametrically opposed to the delivery of electricity and reduces the purpose of the utility, putting those who depend on consistent electric service, and the economy, at risk. Burying transmission lines is one solution to prevent fires during windstorms, however it comes with a host of challenges[3]. First, it is extremely expensive. Bloomberg New Energy Finance found that burying PG&E's overhead transmission lines could cost up to $67B[4]. The majority of this cost is associated with digging through large swaths of area. Identifying and fixing faulty underground transmission lines is also costly, and the fact that utility workers may have to dig to fix the faulty line will only extend outage duration. Second, burying lines underground takes a long time, and according to the California Public Utilities Commission, at today's pace, moving all of California's utility lines underground would take 1,000 years. Finally, burying lines is environmentally invasive.

Third, today's top-down bulk power system planning processes are not sufficient to meet society's resilience needs.

This leaves significant portions of future power system planning investments unable to meet the local needs of the energy consumers. Additionally, local resources that can lower costs across the power system are not being maximized. These resources can play a vital role in keeping society powered when transmission lines have been de-energized.

Based on these indicators, we assume that:

1. A transition to a more distributed and renewable grid is necessary.
2. Shutting off electricity to ratepayers is not an acceptable solution.

We see an opportunity, as diverse and interdependent stakeholders, to accelerate the transition to this lower cost and more efficient energy future. Sunrun seeks to work with any and all toward that common goal.

[3] Baker, David R. "Underground Power Lines Don't Cause Wildfires. But They're Really Expensive." SFChronicle.com, San Francisco Chronicle, 21 Oct. 2017, www.sfchronicle.com/bayarea/article/Underground-power-lines-don-t-cause-wildfires-12295031.php.
[4] Ibid.

Vision

We can create an electricity grid that serves the customer, the community, and the economy.

This will be done through:

- Clean and sustainable electricity generation.
- Inherent resiliency in the transmission and distribution (T&D) system, down to the municipal and and customer levels.
- A lower-cost system to build and maintain.
- A lower contribution to the incidence of fire and the associated societal burden.

The vision statement implies the ability to:

- Shift the majority of customer electricity consumption to on-site renewable generation.
- Shift enough generation to distributed points on the grid. This will support local load-shaping needs during normal operations and multiple segmented grids during periods when resilience is most needed.
- Temporarily disconnect distribution from transmission, as well as individual distribution circuits within the distribution network, when needed for general resilience (unplanned outages) and fire avoidance (planned outages).

Limitations of Solutions Today

Today's electric grid is a mesh network (implying it is distributed and segmented); it lacks the ability to electrify segments -- such as neighborhoods -- without using large, centralized generation and the associated transmission networks. Although traditional on-site fossil fuel generation, such as gas generators, exist, they are polluting, noisy, and require refueling.

Currently, there are two viable solutions for clean, distributed outage support on the consumer level:

- **Home or Business Scale:** Rooftop solar and battery storage supports the utility and customer when they are grid-connected, and the customer when they are grid-disconnected during an outage. However, it does not currently have the capability to support a larger utility segment on the distribution grid during an outage.
- **Campus Scale:** Campus microgrids do not currently have the capability to support an external distribution grid segment in the case of an outage.

Neither of these solutions are currently capable of maintaining an electrified segment where the distribution grid is separated from transmission grid. This is because the power system does not plan for resilience operations of a segmented grid, nor does it have sufficient capacity of DERs coordinated with planning and operations of the grid. Therefore, all of today's solutions can only serve their own customers and duplicate the effort of disconnecting from the larger grid to form their own segment. Those outside the segment will not be re-energized during power outages, and thus will not have access to power. Since there is not currently a way to share electrons with neighbors or other customers connected to the same distribution line segment, these solutions do not provide full resilience to those affected by the de-energization of transmission lines in fire-prone areas.

SCENARIO 1	SCENARIO 2	SCENARIO 3
Normal Operation	**Community Backup**	**Individual Backup**
Utility Support	Utility Support	Utility Support
Transmission & Distribution	*Distribution Only*	None
Solar + Storage Behavior	Solar + Storage Behavior	Solar + Storage Behavior
Grid Services & Time-of-Use	*Share Power**	Individual backup
	** DERs cannot share power during outages today*	

Only scenarios 1 & 3 are possible today. In the future, widespread rooftop solar and battery storage on individual homes could be leveraged to share power and backup other ratepayers during a transmission outage.

Proposed Future

For the future we propose and discuss further below:

- **Distribution Network Disconnection:** To disconnect distribution substations from the transmission grid during planned outages, and autonomously disconnect when transmission outages are detected during unplanned outages.
- **Distribution Network Segmentation and Re-energization:** To form an independent distribution grid from energy stored in batteries (and other technologies like fuel cells and flywheels) at the distribution substation, allowing for the re-energization of individual distribution circuits on the local level.

- **Distributed System Operators (DSO) Management:** To coordinate load shaping and grid service needs during normal grid conditions, and segmented grid operations during abnormal grid conditions, ensuring power quality and reliability is maintained within existing utility standards.
- **Autonomous DER Coordination Capability:** To coordinate DERs along the distribution network with each other and the segmented distribution grid, overseen by the DSO, and to support the segmented distribution network.
- **Marketplace for Segmented Grid:** For participants along the segmented grid to optimize resource allocation via instruments like price signals and transactive energy.
- **Diversity of DERs:** For systems on the distribution network to include intelligent load control, solar and storage, electric vehicles, fuel cells, etc.
- **Distribution Network Re-connection:** For the distribution network segment to reconnect to the transmission grid.
- **Transmission Networking:** For groups of distribution substations to rejoin transmission pockets/segments as it makes sense or is necessary to provide additional resilience.

To maximize resilience and minimize cost to the ratepayer, the DERs along the distribution circuits would be significantly greater in power and capacity than the initial battery bank, sited at the utility, which will be used to start the re-energization process. This will present new technical challenges, all of which can be solved with technology that is available today. That is to say: no fundamental breakthroughs in power distribution and generation need to occur, although there will be patentable solutions developed through this work.

This system redesign would involve all key stakeholders in the electric supply chain. At a minimum, this would include:

- ISOs and RTOs (transmission dependent)
- Utility and DSOs (management and medium voltage network)
- Public Utilities Commission (regulation and standards)
- Standards bodies (certified capabilities and interoperability)
- Substation equipment vendors (protection and blackstart upgrades)
- DER developers/aggregators (deployment and management)
- DER hardware and software vendors (firmware and controls)
- Third party consultants (power systems theory, studies, engineering validation, control algorithm development

Key Considerations for Further Study

We must refine the specifics of implementation through further study. While this paper is not the first to discuss the need for a decentralized system,[5] it can and should act as a springboard for collaboration across the industry.

Some key topics that need to be evaluated include:

- Optimization of substation and feeders during abnormal grid operations:
    - Frequency droop segment, open loop response time, and function coordination.
    - Evaluation of current source and voltage source inverter reponse. Anti-islanding coordinated responses must also be evaluated.
    - Distribution and transmission segment protection coordination.
    - Control algorithm development for the substation battery and other equipment identified in study processes, such as flywheel or fuel cell energy storage.
    - Protection coordination studies in various operating scenarios, including varying directions of real and reactive power flow and varying impedances of generation.
    - Recommend dark start order and timing.
    - Identifying the minimum reliable quantity of substation sited energy storage.
    - Establishing the correct sizing ratios of MW/MWh for substation batteries, new rooftop solar and battery storage DERs, retrofit or new solar only projects, other forms of DERs, and any onsite firm generation as needed.
    - Ride-through settings to ensure microgrid segment stability.
- Optimization of substation and feeders during normal grid operations:
    - Economic use cases for the reduction in the marginal price of power.
    - Distribution level optimization for the reduction in wholesale services procured and future infrastructure spend.

[5] O'Neil, Connor. "From the Bottom Up: Designing a Decentralized Power System." NREL, National Renewable Energy Laboratory, https://www.nrel.gov/news/features/2019/from-the-bottom-up-designing-a-decentralized-power-system.html.

Technical Implementation

The deployment of substation-sited energy storage, customer-sited DERs along the distribution network, advanced controls, and upgrade of utility switchgear and protection, can enable the creation of self-sustaining distribution segments:

- Distributed islands or segments would be formed at the substation level, with capability to disconnect and reconnect from the transmission grid in coordination with distribution system operator.
- The utility would deploy energy storage and islanding switchgear and protection at the substation level with enough capacity to re-energize feeder circuits within the distribution network, giving DERs along the feeder circuits enough time to keep the segment electrified.
- The majority of rooftop solar and battery storage generation will be customer-sited by home and commercial solar developers (assuming 80%+ penetration due to benefits like customer energy cost savings and improved resilience). DERs would be coordinated to the DSO distribution substation energy storage with appropriate controls and capacity able to bear, at minimum, the burden of sustaining the feeder.
- Re-energization of remaining feeders will happen in sequence with the substation energy storage and DERs along the distribution network.

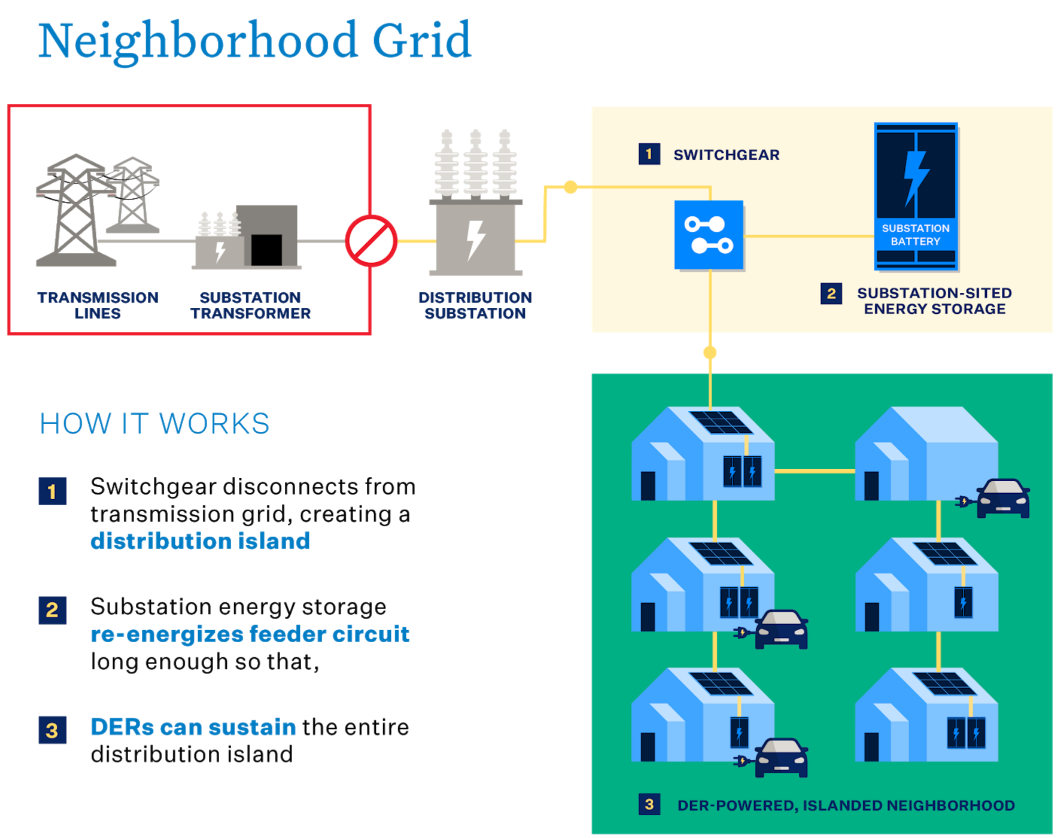

Exhibit 2: Example substation with minimal substation-sited storage for forming distribution segment, customer-sited individual feeder generation greater than feeder load, and many multiples of total feeder generation versus substation-sited storage.

Substation Level Development

To enable such a scheme, the following capabilities will likely be required:

1. Substation energy storage that can operate in voltage source mode with the utility (supports utility voltage, maintains frequency, battery idle during normal operation).
2. Substation energy storage with grid-forming capabilities in the event of a transmission outage, that can enable frequency droop profile and control algorithms that are compatible with DERs along the distribution network.
3. Switchgear and relay protection capable of islanding operations and fault masking detection.

DER Level Development

To enable such a development, existing rooftop solar and battery storage DERs could be modified with minimal firmware and controls adjustment to support a segmented system:

- In which DERs operate in current source mode with the DSO (which pushes current, normal operation defined by consumer charging and discharging profiles).
- In which the firmware for DERs will certify a new standard which, 1) enables DERs' contribution to the grid via frequency droop with open loop response time coordinated with substation battery response and, 2) allows for fast return to service (few seconds) as certifiable with current IEEE 1547-2018 testing standards.

In this scheme: 1) anti-islanding is preserved, allowing the DSO to control whether or not the distribution circuits are energized and, 2) DERs contribute to maintaining the segment at a higher priority than customer normal operation.

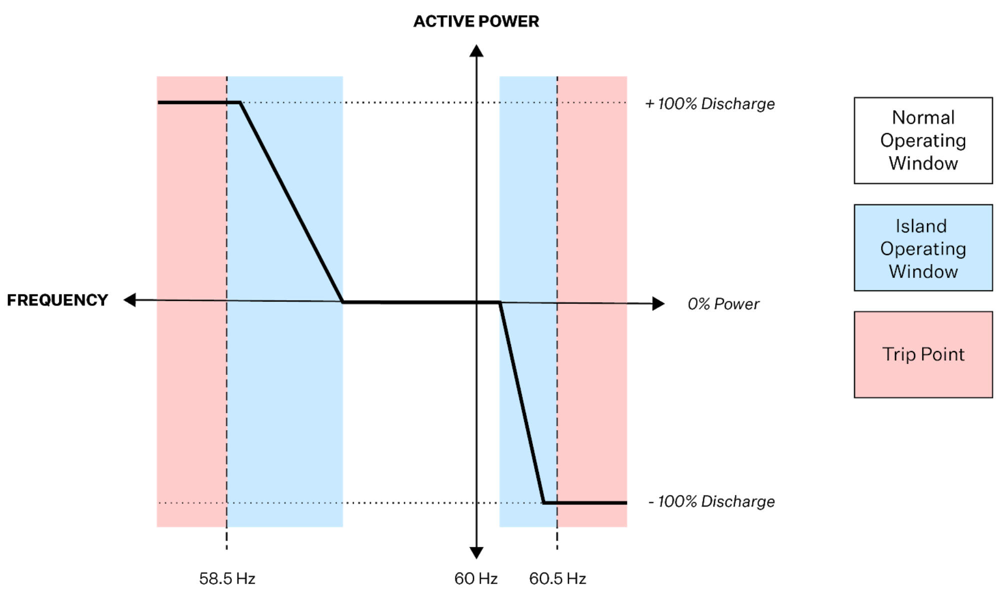

Exhibit 3: Example DERs frequency droop curves with no modification of customer use case in normal operation, response to distribution energy storage in segmented operation, and standard trip points for over and under frequency events.

Conclusion & Follow Up

Implementation of such a solution would need cooperation, support, and capital across a wide range of the electric industry.

In particular, this will require:

- **The Formation of an Industry Working Group:** Similar to the California Smart Inverter Working Group, a cross industry team should be formed to advance the day-to-day development of the solution.
- **Analysis of Economics & Technical Implementation:** A formalized evaluation of the economic merits of such a solution, including actual implementation costs, benefits from grid services, value of lost load, and the impact to ratepayers should be considered. Such a recommendation will also require the verification of the technical concepts and the sizing of batteries and solar.
- **Adherence to Certification Standards:** Substation and DERs firmware standards must be put in place, which could be delivered through UL1741, Rule 21, and other interconnection standards enforced by the Public Utility Commissions.
- **A Pathway for Utility Substation Upgrades:** The commission will need to approve a plan enabling utilities to deploy distribution substation switchgear, protection, inverters, and batteries, all at the lowest possible cost to ratepayers.
- **Economic Support for Consumer Adoption of DERs:** To reach penetration levels of DERs on feeders able to sustain an island will require many rooftop solar and battery storage systems along individual utility feeders (potentially requiring the majority of homes to have this technology). A rebate or other payment incentive along with customer marketing can ensure sufficient deployments.
- **A Field Pilot:** A pilot program must be launched to prove out the first implementation of the Clustered Segmented Grid Concept.

There is a real opportunity to modernize the grid, keep families safe, and reach our climate goals all while benefiting stakeholders. This solution will require a wide breadth of knowledge, innovation, and collaboration from some of the brightest minds across the entire electric industry. Please provide your feedback and work with us to make it happen.

Acknowledgments

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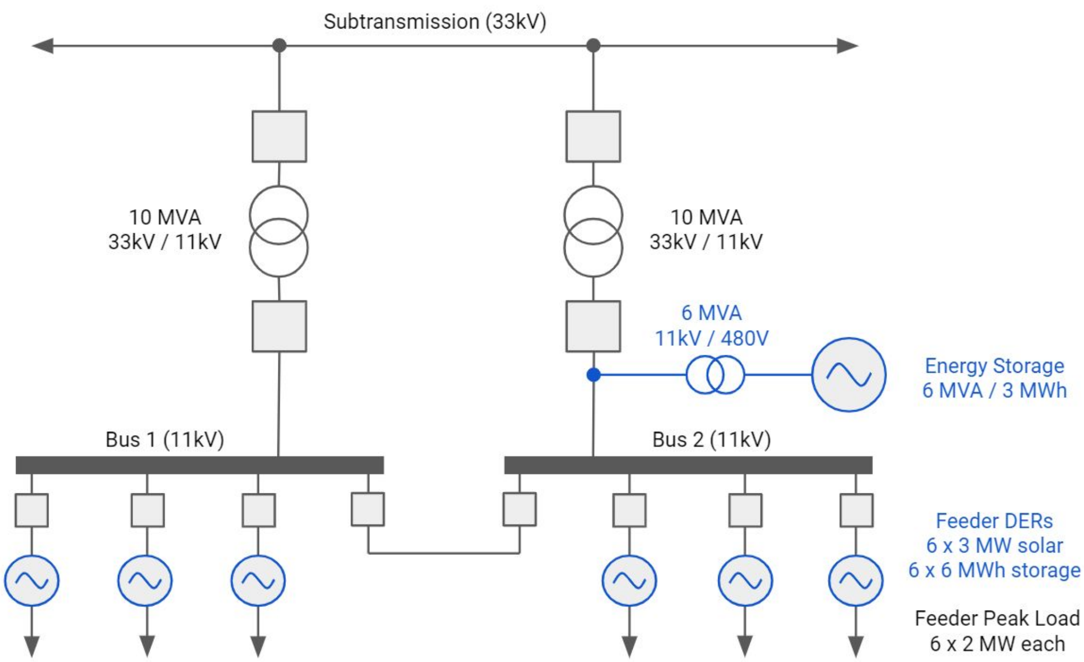
Appendix

Example Engineering Diagram of Substation and Distribution Circuit Design



Example substation with minimal substation-sited storage for forming distribution segment, customer-sited individual feeder generation greater than feeder load, and many multiples of total feeder generation versus substation-stied storage.

Method of Forming Segments in Dark Start Operation

Proposed method of forming distribution segments roughly follows the existing utility re-energizing procedures:

1. The switchgear disconnects the transmission grid
2. The feeder switchgear opens all circuits
3. The substation energy storage forms a distribution segment with no load in voltage source mode
4. The feeder switchgear closes a first designated “lowest load” circuit
5. Substation energy storage regulates segments within the frequency droop settings of the segment’s operating window

6. Substation energy storage waits for DERs to come online and respond to segment frequency droop profile
7. Feeder switchgear closes the second circuit
8. Repeat steps 4 to 6 for N number of circuits until all circuits are energized
9. Following transmission outages, clustered grid is de-energized and reconnected.

Due to the higher incidence of feeder sided generation to load, energizing each additional feeder leads to additional stability of the multi-feeder island, creating an inherently resilient system.