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Control of Embedded Bulk Electric Storage Networks for Operational Flexibility and Grid Resilience

June 2021

JD Taft

U.S. DEPARTMENT OF ENERGY

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Executive Summary

When bulk energy storage units are located at Transmission/Distribution interface substations system-wide and operated collectively, such an arrangement can be made to improve intrinsic grid operational characteristics and dynamic grid behavior. This schema requires specialized but practicable control of the storage devices, along with appropriate grid observability (sensing capability). The method is aligned with present approaches to transmission system observability via synchrophasor measurement and with modern architectures for the use of storage as core infrastructure. Control of the storage units in such an arrangement is unlike control of storage used for grid services. It is more akin to primary and secondary real time grid control – it operates on grid sensor data and must function on time scales far too short for market-based or security constrained economic dispatch methods.

This document describes four nested control schemes operating on different time scales. They enable operation of Coordinated Storage Networks to improve intrinsic operational flexibility and resilience of the grid so as to facilitate integration of variable (stochastic) resources on a regional scale in an equitable manner. These control schemes are not market dispatch functions for ancillary services, rather they use real time grid state feedback and advanced control algorithms that function autonomously inside the grid.

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1.0 Storage as Core Infrastructure

The purpose of integrating storage into core grid infrastructure is to provide the grid with a dynamic functionality common to most complex systems but which has been lacking in electric power systems.

1.1 Buffering in Complex Systems

Buffers are mechanisms for decoupling flow variations, especially random or unpredictable variations. The presence of a buffer provides a system with “springiness” or “sponginess” that makes it resilient to a variety of perturbations. In fact, lack of such springiness is a resilience vulnerability.

Most complex systems have some form of buffering. Communication systems have “jitter buffers” to even out the flow of data bits in communication network transmission. Computing systems have various kinds of data buffers that operate on differing time scales.[1] Logistics systems have buffers – they are called warehouses. Water and gas systems have buffers – they are called storage tanks. In each case, the buffer is some form of storage that evens out irregular flows, thus reducing or eliminating the impact of volatility (fluctuation or interruption) in source or use.

Grid energy storage receives energy in the form of electricity from the power grid and then later either returns it to the grid as electricity (“reflexive”) or converts it to some other use (“transitive”) as Figure 1 illustrates.

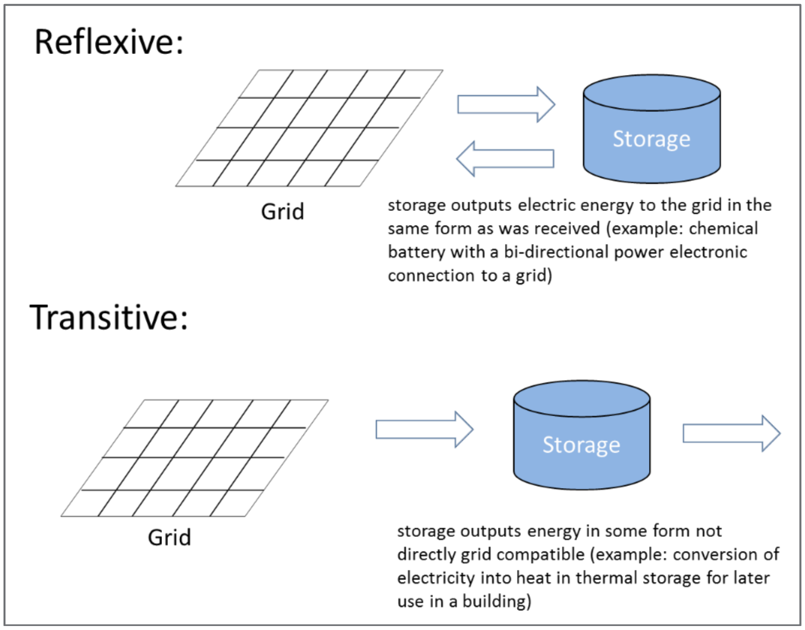

Figure 1. Storage Process Model Definitions

[1] Some data may persist only for only very short periods of times and be stored in small volatile memory buffers, whereas other data may persist for years and be stored in non-volatile databases.

The use of storage as a grid operational tool focuses on reflexive storage that can operate on fast (short) time scales with considerable functional flexibility. This leads to the concept model for grid energy storage shown in Figure 2, which has three major elements: the energy storage device, advanced controls,[1] and a flexible grid interface.

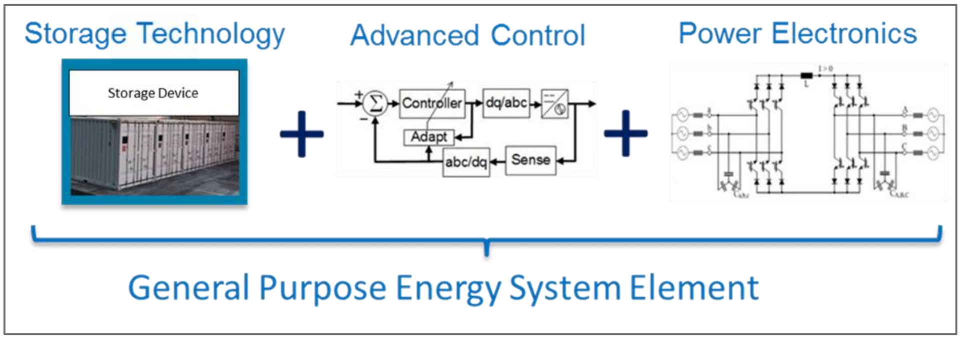

Figure 2. General Purpose Grid Element

Note that while it would not be unusual to consider electrochemical batteries for the storage elements, implementations based on other technologies are possible. The reason for the power electronics element is that while the electric power grid uses alternating current (AC) most storage elements operate with direct current (DC). Power electronics provides the means to connect DC and AC systems and offers much flexibility in terms of actual control functions. Real storage devices also have storage management systems, communications interfaces, and other components, but the three elements shown in the diagram are the basis for grid energy storage that can be used as a general-purpose grid element.

1.2 Storage Embedded in Infrastructure

A *Coordinated Storage Network* (CSN) is a systemic deployment of bulk reflexive storage at Transmission/Distribution substations, with the storage units electrically connected to a power bus (engineering details determined in part by the substation bus structure). The deployment is *system-wide*, not just at a limited number of selected substations. Storage devices are located at every T/D interface substation.[2,3] Figure 3 illustrates the concept for the IEEE 39 bus system.

---

[1] Advanced storage control is multi-modal, so that the storage device can be used in several ways and the operating mode can be changed very quickly and automatically to meet changing grid conditions.

[2] R O'Neil, A Becker-Dippmann and JD Taft, The Use of Embedded Electric Grid Storage for Resilience, Operational Flexibility, and Cyber-Security, PNNL-29414, October 2019, available online: https://gridarchitecture.pnnl.gov/media/advanced/The_Use_of_Electric_Grid_Storage_for_Resilience_and_Grid_Operations_final_PNNL.pdf

[3] GMLC Grid Architecture Team, Grid Architecture Specification: Advanced Bulk Power System Reference Architecture, PNNL-29440, November 2019, available online: https://gridarchitecture.pnnl.gov/media/zip/Advanced_BPS_Reference_Architecture_package.zip

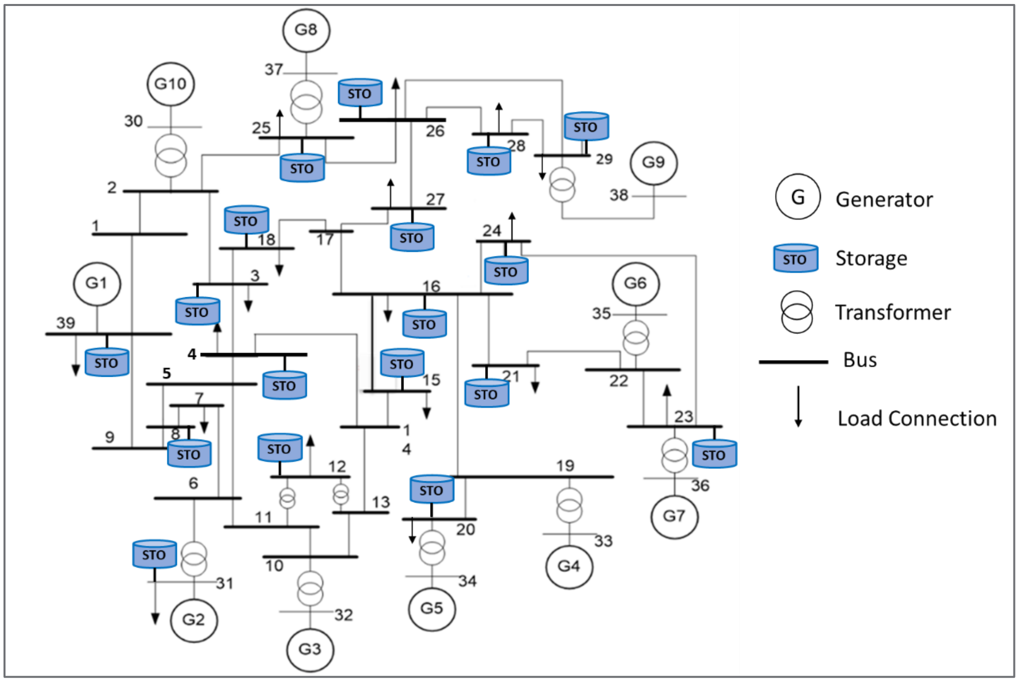

Figure 3. CSN Deployment on the IEEE 39 Bus System

The storage core component is a subsystem consisting of a storage element, inverter and grid interface, local control, communications interface, and phasor measurement unit (PMU). The storage subsystem is shown in Figure 4 inside the dashed box.

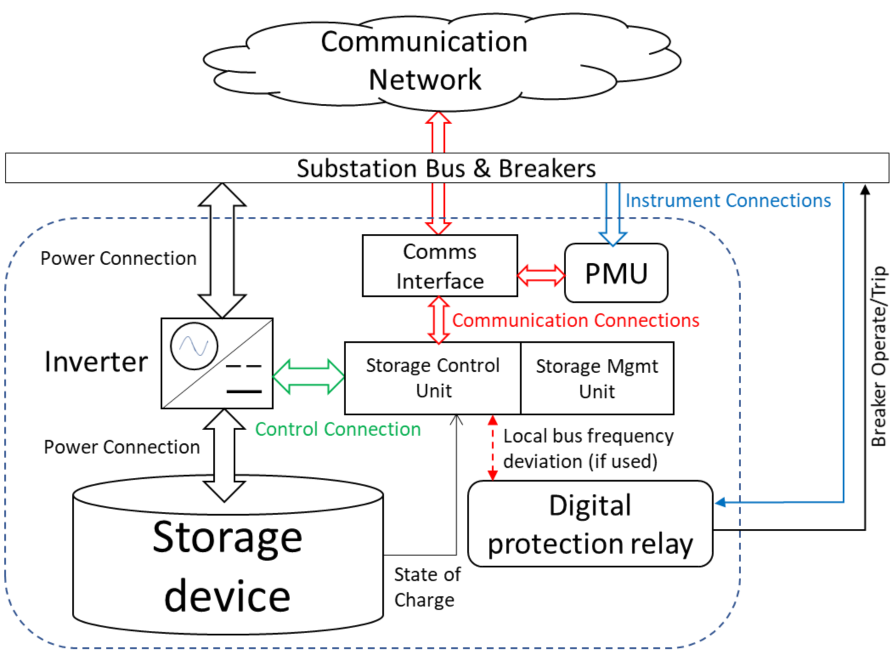

Figure 4. General Model for a Single Substation CSN Element

Control of a CSN is not the same as control of an individual storage device used for grid services or point reliability improvement. A CSN cannot be managed using market clearings and dispatch due to two factors: the types of signals needed to control the CSN and the very short time scales on which control must be applied.

2.0 Control Algorithms and Time Scales

Use of storage as core infrastructure requires a suite of control algorithms. This section describes several of them.

2.1 Volatility Decoupling Control

The volatility control minimizes power flow volatility at the substation buses by providing power injections from the storage devices. Control for the storage devices is in the form of a state feedback regulator, as shown in Figure 5.

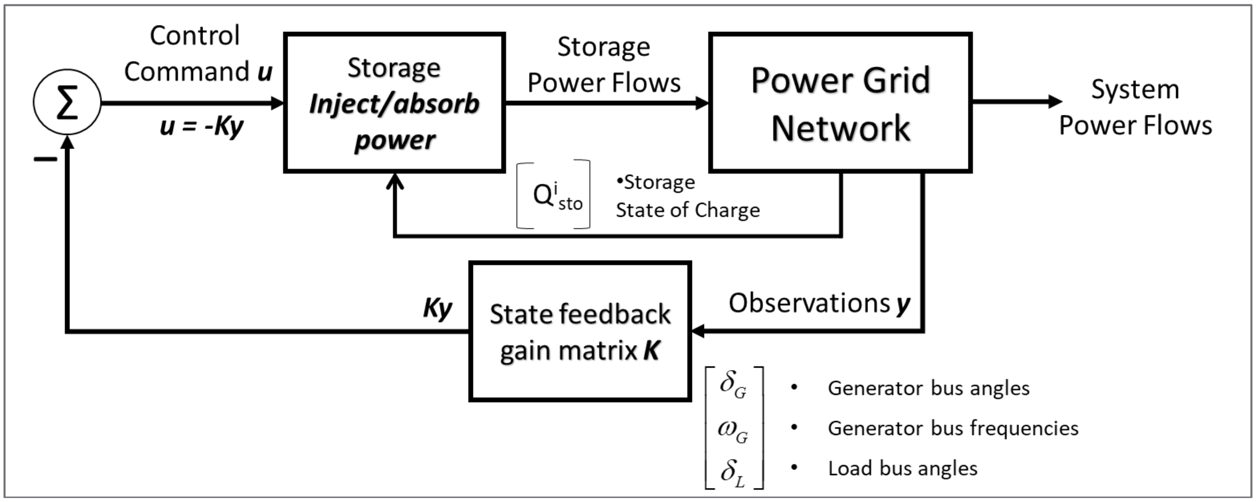

Figure 5. Volatility Regulator Control

An optimal control algorithm exists for this problem.[1] The feedback comes from three types of signals: generator bus angles, generator bus frequencies, and load bus angles. These three classes of signals react to transient power flow conditions. The control has the effect of creating an optimal observer for the disturbance signals – the control for the storage devices is the negative of the disturbance signals.

Figure 6 shows an example of a substation load bus volatility disturbance signal and the resultant optimal battery control signal. The optimal control functions to observe (reconstruct) the load disturbance (around a base value) and converts that into the battery signal that will exactly compensate for the volatility. This result is from a power flow simulation.

[1] S P Nandanoori, J Lian, et. al, Sparse Control Synthesis for Uncertain Responsive Loads with Stochastic Stability Guarantees, PNNL-SA-156076, January 2021. Pre-publication copy available on request.

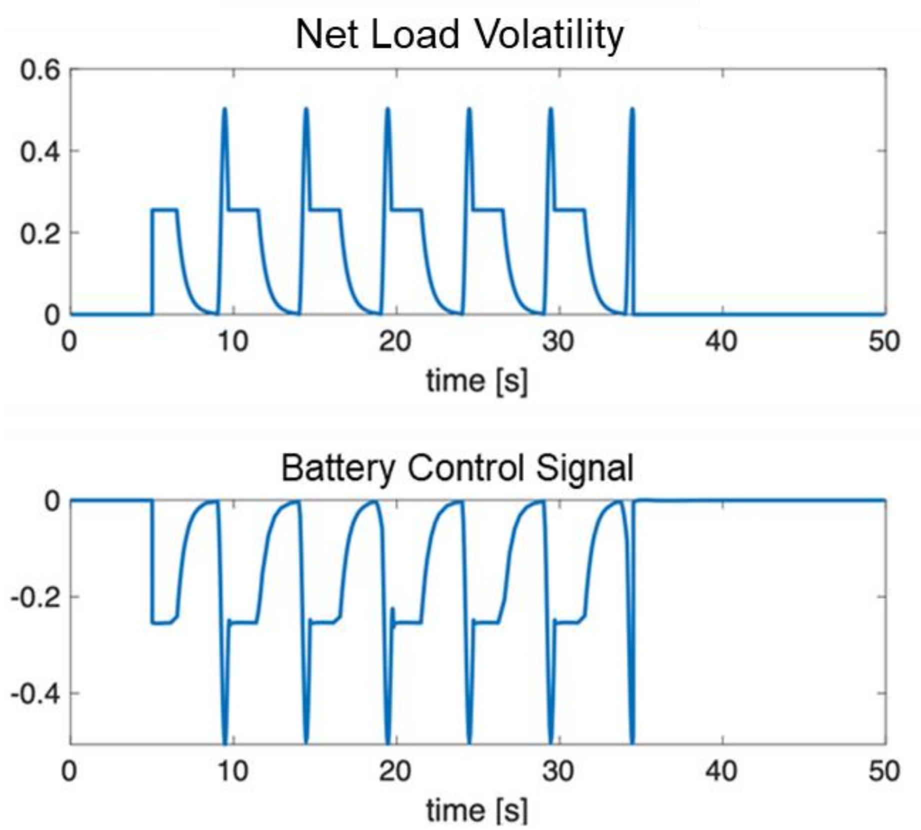

Figure 6. Load Disturbance and Recovered Optimal Battery Control

Figure 7 shows an example of the effect of applying this type of storage control on net load seen at the substation bus. While the loads volatility is unchanged (the control has not modified the load behavior) the net load seen at the substation load bus is regulated to be flat. This prevents the volatility from propagating through the system, which is the objective of this aspect of CSN control.

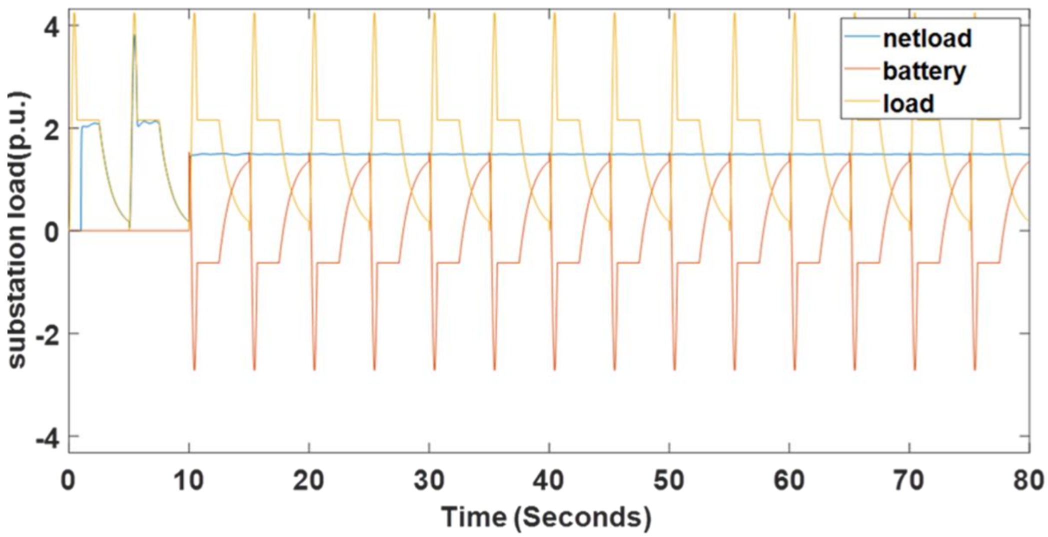

Figure 7. Battery Regulation of Bus Load

The optimal control shown above presumes a static value for substation loading. In order to use the algorithm in a practical setting, we introduce a reference feedforward, as shown in Figure 8.

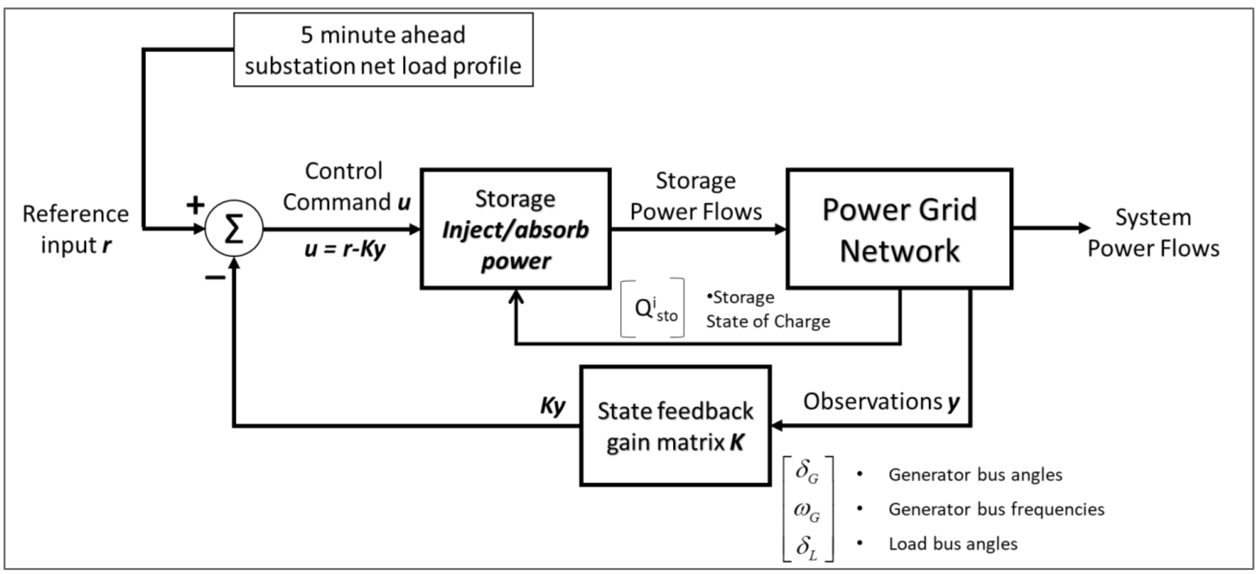

Figure 8. Volatility Regulator with Reference Feedforward

With this reference feedforward, the control can operate in a quasi-static mode, following a forecasted substation load profile while providing the necessary shock absorber effect needed for decoupling of power flow volatility. Note that the volatility involved occurs on a very short time scale with respect to the rate of change of the load profile. Not shown here is the means to keep the storage State of Charge (SoC) near the 50 percent level on a long-term average basis. This can be done by injecting a slow bias into the storage control signal, using the SoC feedback signal.

2.2 Inertia Augmentation and Control

System inertia in electric power systems has historically derived from the angular momentum of heavy rotating machines used to generate electricity. The physics of system inertia shows that the effect is related to the rate of change of frequency (ROCOF), where the frequency involved is the system frequency (nominally 60 Hz in the US).[1] Much work has been done to show that properly controlled power injections can have the same effect as actual rotational inertia and so have been termed synthetic or pseudo-inertia methods.[2,3] The inertia effect operates on very short time scales.

With the proper feedback signals, CSNs can augment or otherwise modify system inertia. The term ”otherwise modify” means to change the apparent system inertia under controlled conditions to suit grid operation and stability purposes – possibly including reducing system inertia at times.

Figure 9 shows a CSN control structure suitable for inertia regulation.

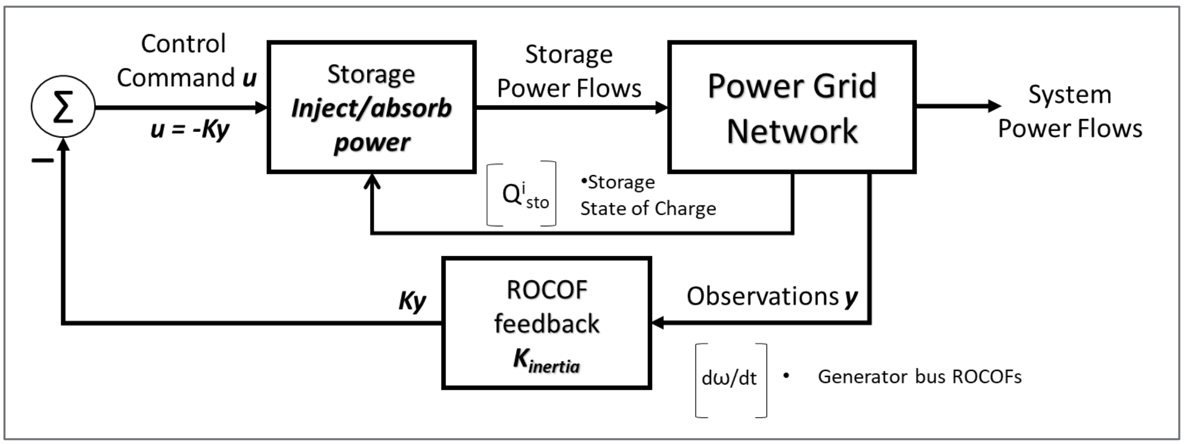

Figure 9. CSN Inertia Regulator Control Structure

It may be feasible to substitute substation bus ROCOF measurements for generator ROCOF measurements, thereby making the inertia control at each CSN unit able to function in a completely localized autonomous manner.

For this control, the means to adjust or modulate inertia augmentation via storage control is adjustment of the ROCOF feedback gain parameter, as shown in Figure 10.

[1] H Thiesen, C Jauch, and A Gloe, Design of a System Substituting Today's Inherent Inertia In the European Continental Synchronous Area, energies, July 2016, available online: www.mdpi.com/1996-1073/9/8/582/pdf
[2] Pieter Tielens and Dirk Van Hertem, *Grid Inertia and Frequency Control in Power Systems with High Penetration of Renewables*, available online: https://www.semanticscholar.org/paper/Grid-Inertia-and-Frequency-Control-in-Power-Systems-Tielens-Hertem/1cd19e3ae4b3ff6919570cf6faa693a13d21652a
[3] M Torres and L Lopes, Virtual Synchronous Generator: A Control Strategy to Improve Dynamic Frequency Control in Autonomous Power Systems, April 2015, available online: http://file.scirp.org/Html/5-6201497_30602.htm

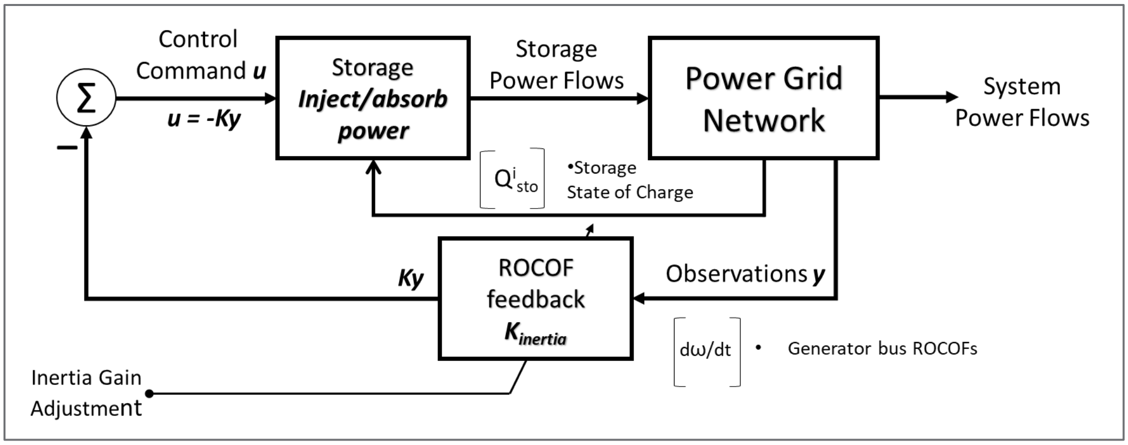

Figure 10. General CSN Inertia Control Structure

2.3 Short Term Planned Event Management

Control of CSNs for short term forecasted events resembles trajectory planning. A method investigated for DER management can be adapted to CSN control without the shortcomings inherent in the DER approach.[1] Figure 11 shows the structure for such a control. Here the forecast for the substation power flows indicates upcoming events that depart significantly from the usual power flow profile. With such a forecast, it is possible to operate the storage units in a non-causal manner. Because the primary driver is the forecast, the only feedback is the storage devices' SoCs. The rest is feedforward.

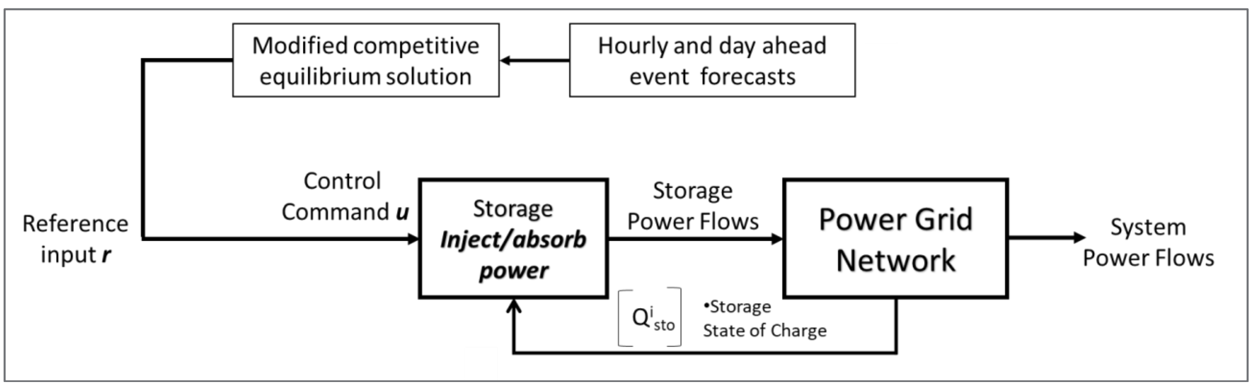

Figure 11. Hourly/Day Ahead Forecasted Event Control Structure

Figure 12 (adapted from Meyn, et. al,[2]) illustrates a synthesized example that uses a forecasted load event and makes use of a competitive equilibrium solution to determine the storage control signals. In the original paper, the controlled devices are controllable loads, but here we hypothesize that the concept can apply to substation storage units that can be charged in anticipation of the planned or forecasted event. It would not be necessary to discover dynamic prices for the storage units, as the cited paper suggests would be needed for loads, since the

[1] S Meyn, et. al, Reliable Power Grid: Long Overdue Alternatives to Surge Pricing, ResearchGate preprint, March 2021, available online: https://www.researchgate.net/publication/350005403_Reliable_Power_Grid_Long_Overdue_Alternatives_to_Surge_Pricing

[2] Ibid, pp 11-13.

CSN elements are not being bid - the mathematical formulation can be adapted to provide the necessary CSN SoC state trajectory.

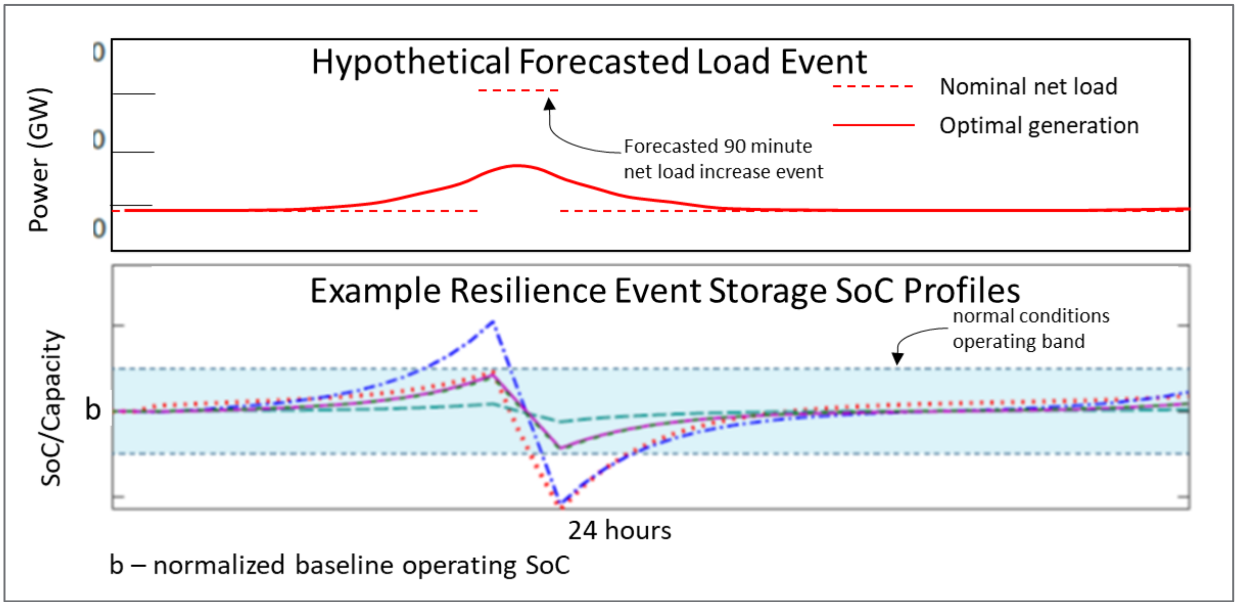

Figure 12. Forecasted Event CSN Control Solution

Note how the solution in this example leads to the storage units charging up in advance of the forecasted event, then discharging during the event, and finally recharging after the event. To the extent that events can be forecasted over a reasonably short time horizon (say, 24 hours), then storage state trajectory plans can be computed and executed.

2.4 Net Load Regulation and Diurnal Net Load Profile Control

Modification of net load at the substation bus (not at the actual loads) can be accomplished with a simple feedback regulator in which the feedback is real power flow at the bus. Figure 13 shows the control structure.

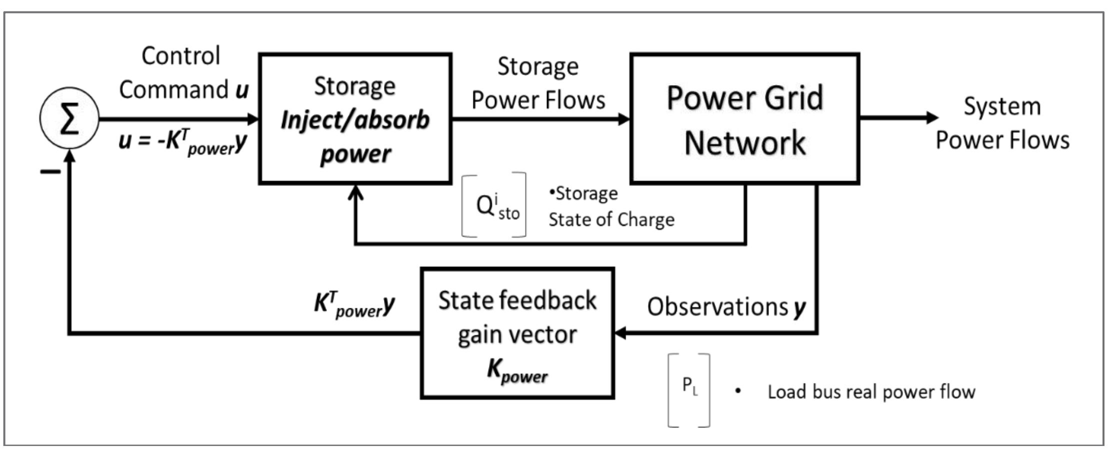

Figure 13. Substation Bus Net Load Regulator

Figure 14 shows the result of a power system simulation of this control at two substations with embedded storage units using this control. In this case, the substation load peaks and valleys were moderated using storage.

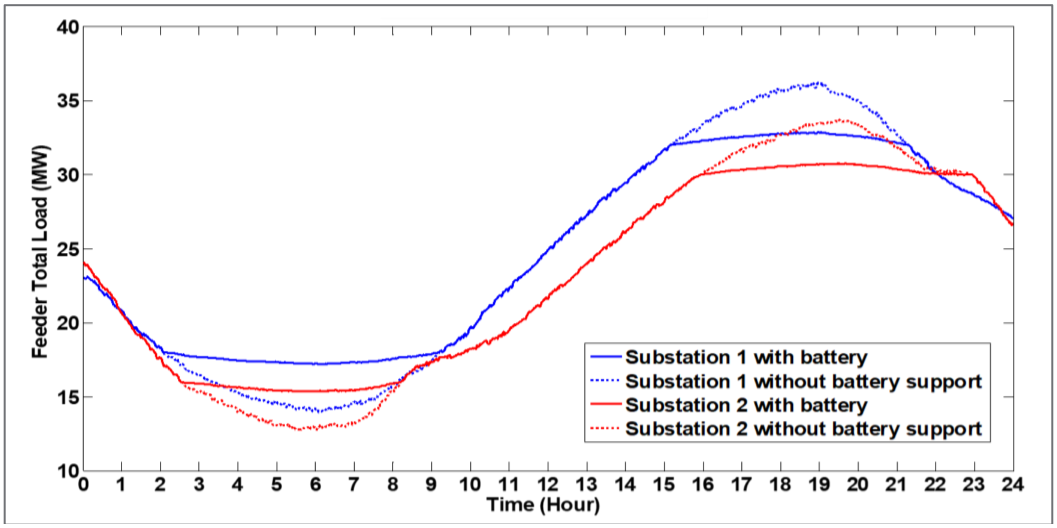

Figure 14. Substation Bus Power Flow Under Regulation Using Embedded Storage

With sufficient storage charge and power flow capacity, it would be possible to completely flatten the substation bus net load. If there is a need to shape the profile in more complex ways, then the same type of reference input structure as was used in the volatility regulator can be employed to perform the load regulation around a quasi-static reference. The technique is the same but would be employed on a different time scale. Figure 15 shows the control structure for shaped bus load regulation.

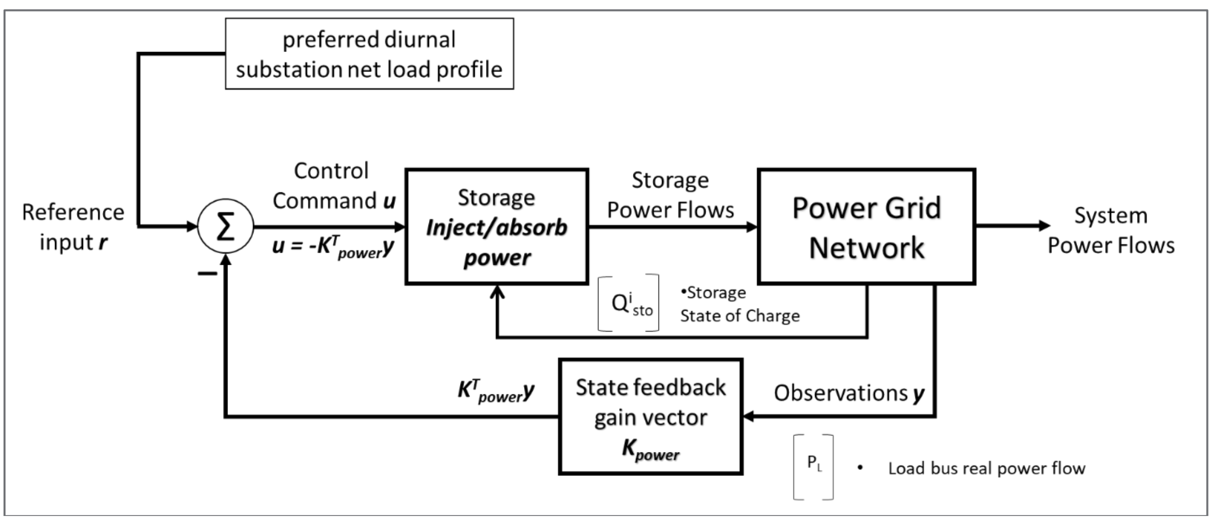

Figure 15. Substation Net Load Profile Control

2.5 Additional Applications

The CSN architecture and control system can be applied to a number of additional operational flexibility and resilience abilities. In each case the appropriate control algorithm and state feedbacks must be specified, but they all fit into the structure outlined above. Some require more sophisticated supervisory control or state trajectory planning – others can operate as state feedback regulators. However, the overall structure remains the same. Additional uses include:

- Avoid/mitigate outages – local supply during outages, including storage charging ("pre-bounding") in advance of resilience events such as severe storms; outage ride-through support for critical facilities and services
- Facilitate source/load matching and source/load decoupling; loosen balance and area frequency control constraints
- Support Electric Vehicle charging (zero outage operation)
- Facilitate microgrid adoption
- Maximize VER energy extraction to avoid curtailment (generation peak shifting)
- Support Distributed Energy Resources integration by managing edge-based volatility
- Enable energy banking/warehousing to facilitate energy networking and congestion management
- Support generation black start – provide initial station power to selected generators and also act as interim load while generation is stabilizing
- Manage volatility exchange between bulk natural gas and electric generation systems – to even out the mismatch between desired constant gas flow and peaking gas turbine generator operation

2.6 General Model

Based on the foregoing, we may employ the general CSN feedback control structure shown in Figure 16. The controls system has a nested loop structure with the inner loop being the direct control of the storage device using storage SoC feedback. The outer loop is a combination of state feedback regulator and reference feedforward. The values in the state feedback matrix depend on the control mode under consideration. In general, the grid state feedback includes generator bus angles and frequencies, load bus angles, ROCOFs, and load bus power flows.

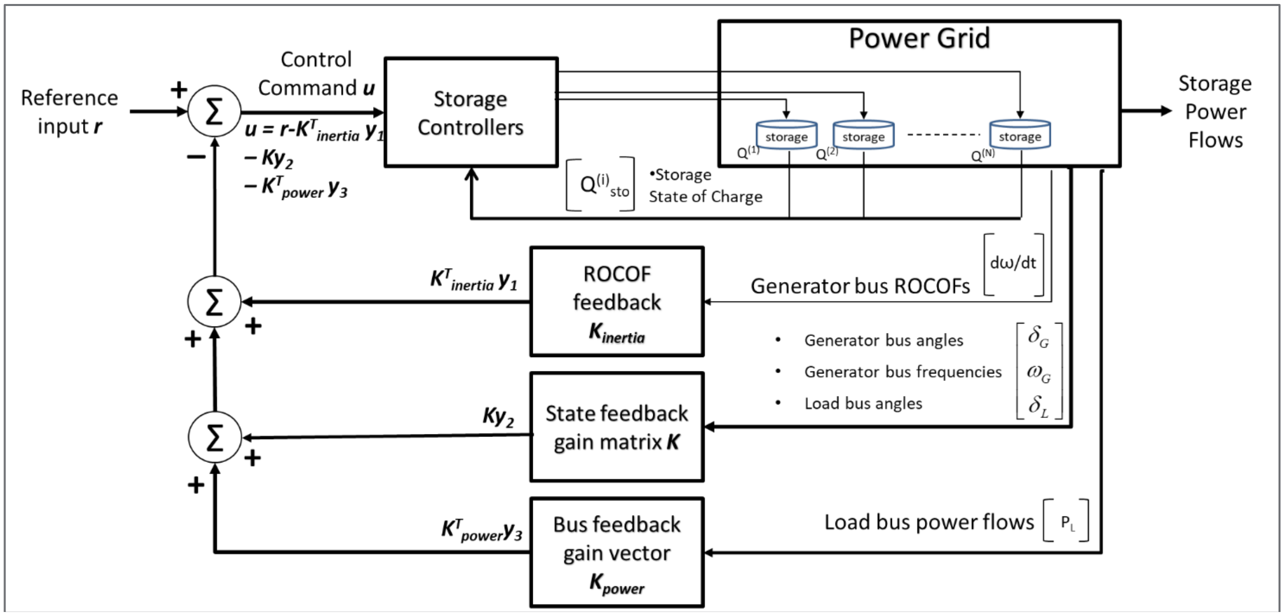

Figure 16. CSN General Control System Block Diagram

Reference inputs may come from a variety of sources, including load and event forecasts, system level setpoints and trajectories, and solutions to system-level optimization problems. The control may also make use of mode-switching – a mode selection mechanism is not shown here.

Figure 17 shows the general control block with three classes of inputs and a set of outputs, one for each of the CSN units.

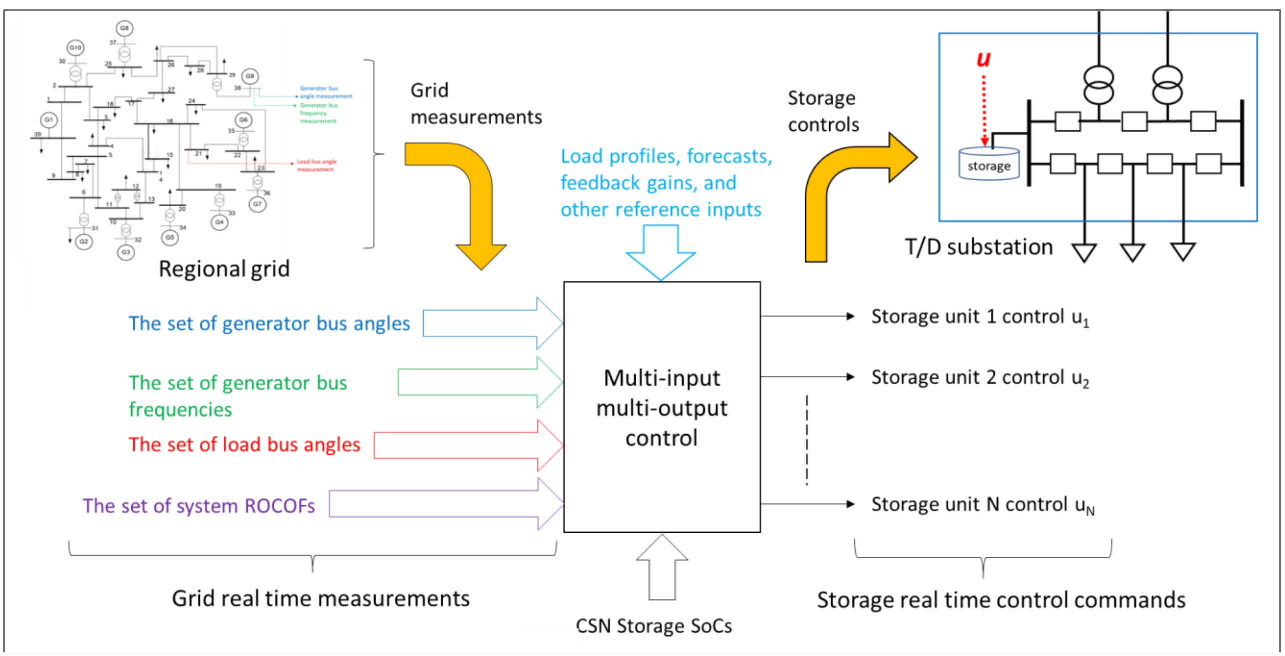

Figure 17. General CSN Control Structure

Depending on the control mode, differing state signals are needed as feedback, and differing reference inputs are needed as feedforward. The differences in the control modes are in the actual control mathematics and time scales on which they operate. These determine the nature of the feedback signals and the reference inputs, but do not change the basic control structure. In general, the entire set of feedback signals and the reference feedforward may be used to calculate each of the storage control signals, but specific algorithms may call for only local substation measurement data, eliminating the need for data transport in those cases.
Table 1 summarizes key characteristics of some of the control modes discussed above.

Table 1. Control Mode Key Characteristics

Control Problem	Grid Dynamics Time Scale	Control Update Time Scale	Feedback
Inertia control	milliseconds to seconds	10-100 microseconds	ROCOF, SoC
Volatility decoupling	sub-second to minutes	10-20 milliseconds	Generator and load bus angles, generator bus frequencies, SoC
Planned event management	15 minutes to 24 hours	seconds	SoC
Diurnal net load profile control	24 hours	sub-minute	Load bus power flow, SoC

3.0 CSN Control Architectures

The previous section identifies a general control structure for CSNs but does not address issues of structure related to implementation. Here we consider several possible structures for the storage network control system implementation.

3.1 Centralized

In the centralized control structure, all state feedback signals are sent to the control center, where all storage control signals are computed. The control signals are then sent to the individual storage units at the substations. Figure 18 illustrates the centralized control structure model.

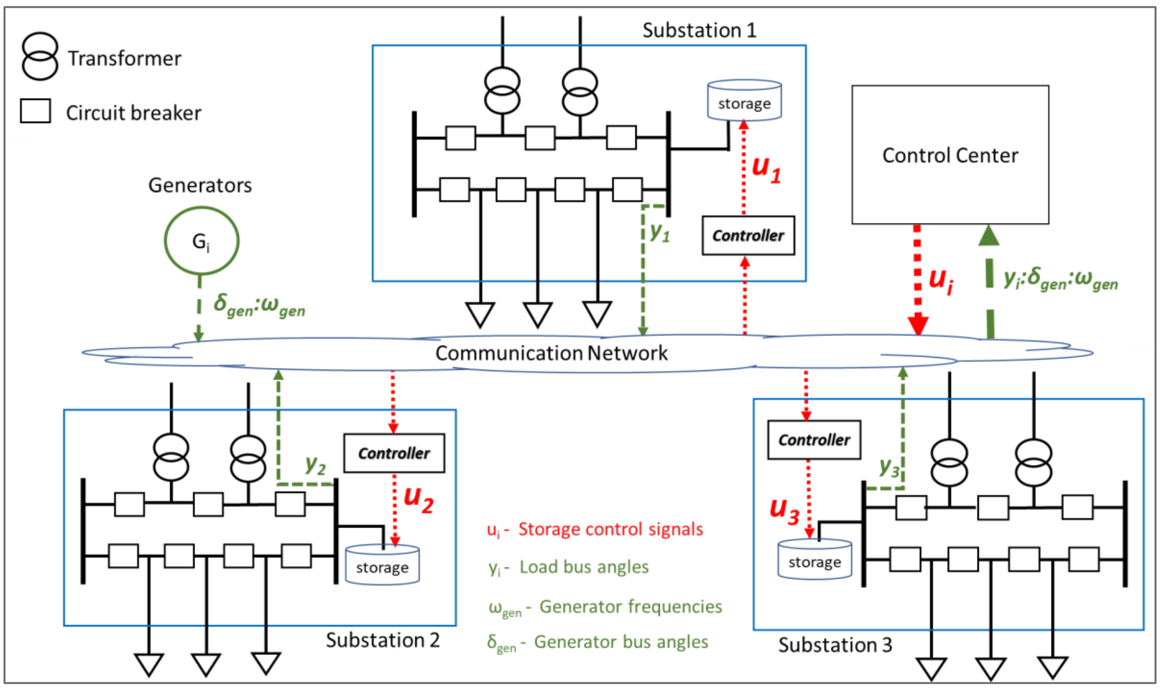

Figure 18. Centralized Control Structure

3.2 Decentralized with Global State Feedback

In the decentralized model with global state, each storage device has a local control unit (in the substation) and each control receives the entire global feedback state individually. Each controller then computes the control for its storage device separately from all the others. Figure 19 shows this control structure model. Note that it i feasible to reformulate some of the control algorithms to function based only on locally measurable state variables, so that transmission of telemetry across a wide area communication network may not be necessary.

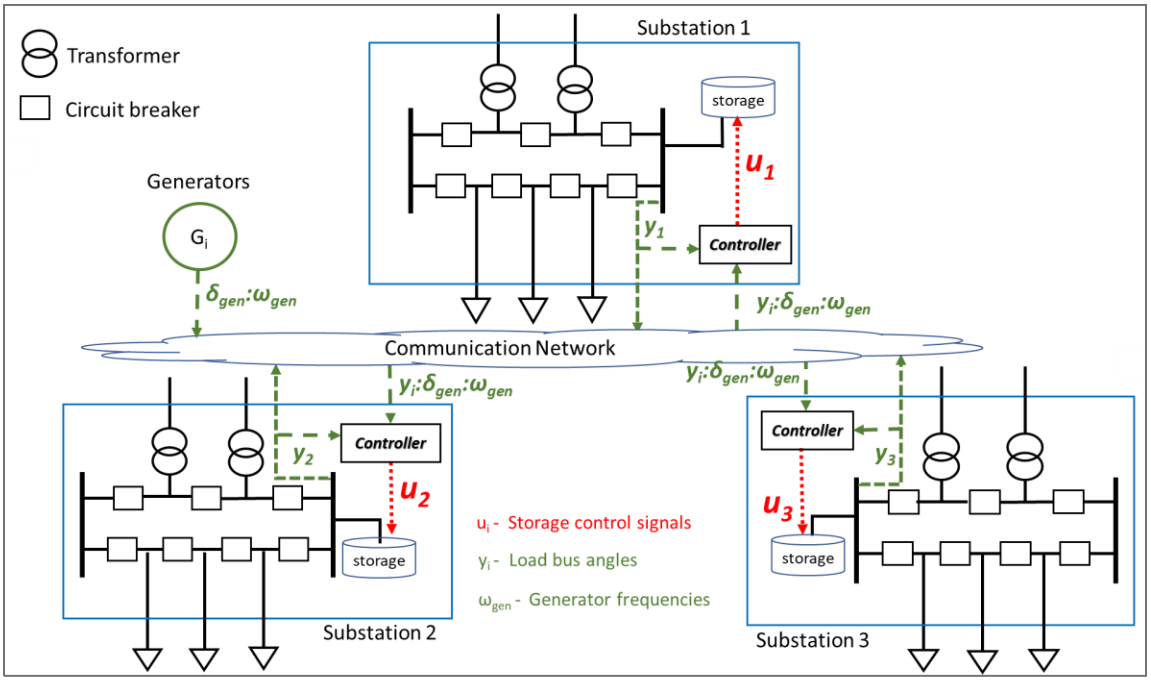

Figure 19. Decentralized Control with Global State Feedback

3.3 Decentralized with Local State Feedback

In the decentralized model with local state only, each storage device has a local control unit (in the substation) and each control receives only local state feedback (load bus frequency, for example). Each controller then computes the control for its storage device separately from all the others. Figure 20 shows this control structure model.

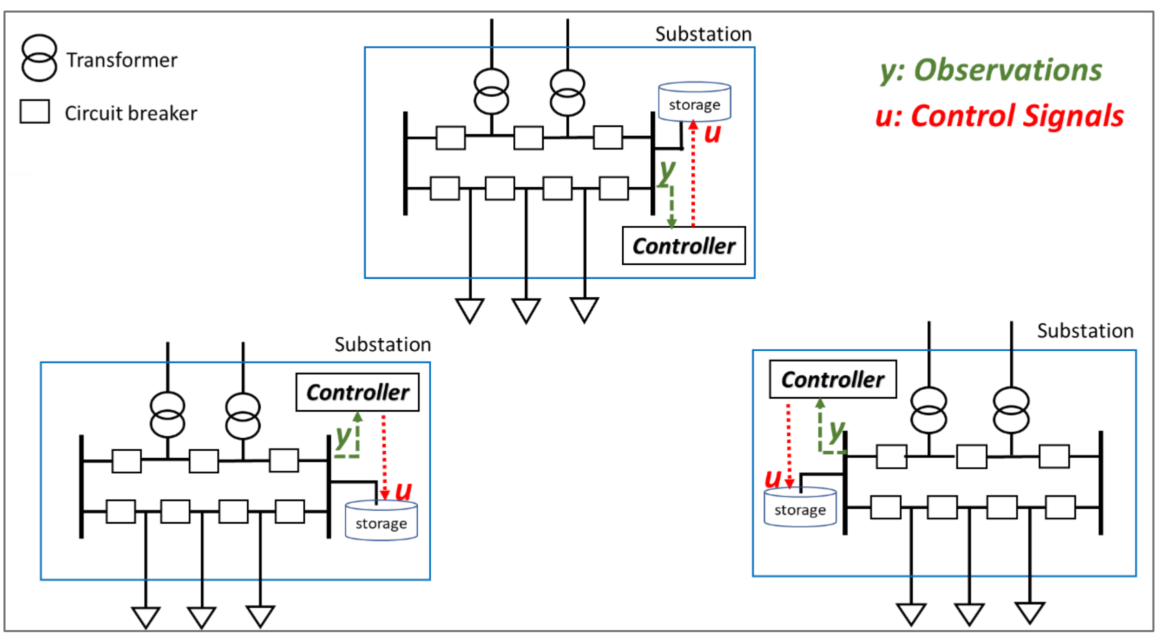

Figure 20. Decentralized Control with Local State Feedback

3.4 Distributed Control

In the distributed control structure, each storage device has a controller and the controllers *cooperate* to determine the control signals jointly by exchanging coordination signals. Each controller has access to local state feedback. Figure 21 illustrates this structure. Note that generator state feedback could be included in this scheme but is not shown in the figure.

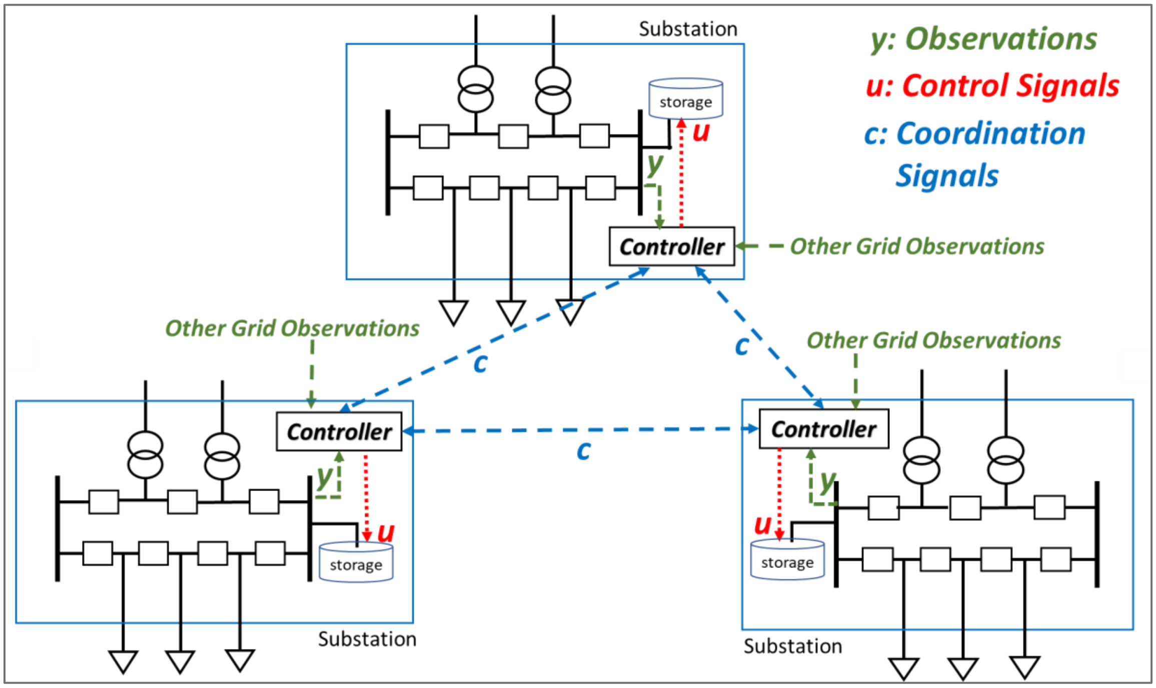

Figure 21. Distributed Control Structure

4.0 Where is Control?

The answer to the question of where CSN control resides depends in part on the control architecture and in part on how inputs are generated, and feedbacks are collected. Clearly, for each form of regulator, the control can reside in the substations, with the storage devices. For the decentralized and distributed architectures, again control resides in the individual substations, although in the case of the distributed control, it must be considered to reside collectively in the substations, not separately and independently, as in the case of the decentralized architectures.

In the case of the fully centralized structure, control could reside in a control center, but that would be problematic from a system resilience standpoint, even with hot backup control centers.[1] This is easily understood in the case of a large-scale event that causes widespread damage to the grid. With the grid fragmented, we want to have the fragments operate as best possible and this means that control should not be fully centralized. This points to a multi-entity cooperative approach, where core feedback control resides in the substations, and then setpoints, profiles, forecasts, and elements of system optimization solutions come from a variety of entities at the bulk power system, regional, and distribution system levels to be coordinated into a deconflicted reference input for the storage network.

The controls can be partitioned to some extent on the basis of time scale and feedback requirements. Considering Table 1, it is clear that regulator control could be partitioned into several nested control loops, just as illustrated in Figure 16, with the fastest loop being innermost. Since control inputs could come from separate entities, the coordination problem is to make sure the operating constraints of the storage device (max/min SoC, max charge/discharge rates) are not exceeded. These limits are device-specific and so should be managed at the substation level.

Inertia gain choice can come from a system operator or balancing authority exclusively. Volatility gain matrices are based on system models and while these are computed from whole system models that derive from system data, the gains themselves are not intended to be adjusted in real time. The gain matrices can come from offline computations done by a system operator or other entity with access to full system and device data.

Forecasted event competitive equilibrium solutions can come from a System Operator, Transmission Operator, or Balancing Authority, but only one of these. Reference input profiles (load curves, generation profiles, etc.) may come from multiple sources and must be either prioritized or merged. As regards energy exchanges when the substation is being used as an energy hub,[2] the management of the energy storage can be done at the hub or by a DSO if one exists or by a Distribution Operator. To the extent that these profiles and uses are competitive or

[1] Jeffrey D Taft, Fundamentals of Structural Analytic Resilience Quantification, PNNL-30423, September 2020, available online: https://gridarchitecture.pnnl.gov/media/advanced/Resilence_Algebra_Foundation_final.pdf

[2] GMLC Grid Architecture Team, Urban Converged Networks Reference Architecture Package, PNNL-29984 1.2.1 v0.3 , May 2020, available online: https://gridarchitecture.pnnl.gov/media/zip/Urban_Converged_Networks_Reference_Architecture_specification_package.zip

in conflict, such issues can be resolved using the layered decomposition approach developed for Laminar Coordination frameworks[1] or via primacy/preemption policies.

[1] JD Taft, Architectural Basis for Highly Distributed Transactive Power Grids: Frameworks, Networks, and Grid Codes, PNNL-25480, June 2016, available online: https://gridarchitecture.pnnl.gov/media/advanced/Architectural%20Basis%20for%20Highly%20Distributed%20Transactive%20Power%20Grids_final.pdf

5.0 Summary Comments

Ultimately, control for CSNs does not reside in one place. This situation is quite common in bulk power systems, where control and coordination operate on multiple time scales, multiple geographic scales, and across multiple entities. It is important to separate the physical elements (storage devices, communications, grid telemetry) from the control and coordination structure to have a clear picture of how such a system operates and integrates with the power grid. Unlike many changes made to the grid made in recent decades, the CSN concept is a *systemic* change, not limited to a single discrete subsystem or service area. This change is aimed at improving the intrinsic characteristics of the system as a whole and hence benefiting the whole community of stakeholders and electricity ecosystem. The system involved in this systemic change (the grid) is comprised of multiple structures that are complex in themselves and which are interconnected in complex ways, making the whole system Ultra-Large-Scale complex. Among these structures are the industry structure and the regulatory structure (the regulatory relationships, not the rules) and these are affected by such a systemic change just as much as the physical infrastructure.

Consequently, traditional approaches to understanding issues of ownership and control, and of benefit flow related to the grid must adapt to a whole system view. The nature of the CSN is that it affects the whole energy delivery system and does not limit itself to just transmission or just distribution, regardless of where the storage devices are located. Also, it is clear from the time scales involved and the nature of the feedback signals and control functions needed that this type of control cannot be accomplished through market-based dispatch mechanisms.

It is important to resolve how to treat CSNs because they are crucial to the wide scale integration of variable and distributed energy resources and because they facilitate energy justice by enabling grid operational flexibility on a systemic and therefore community-wide basis. The systemic nature of CSN operation is something that is pervasive and borderless; its ability to improve system characteristics as opposed to localized ones points toward new ways to think about grid transformation in the 21st Century.

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