Pacific Northwest
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PNNL-30423

Fundamentals of Structural Analytic Resilience Quantification

September 2020

Jeffrey D Taft

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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1.0 Background

Resilience is of vital importance in modern US electric grid planning and operation and yet fundamental gaps exist in the definition, analysis, and application of resilience concepts to grid modernization objectives. The issue consists of three parts: proper definition, methods of quantification, and application to utility processes. At the present, work on grid resilience is ad hoc, as illustrated in Figure 1.

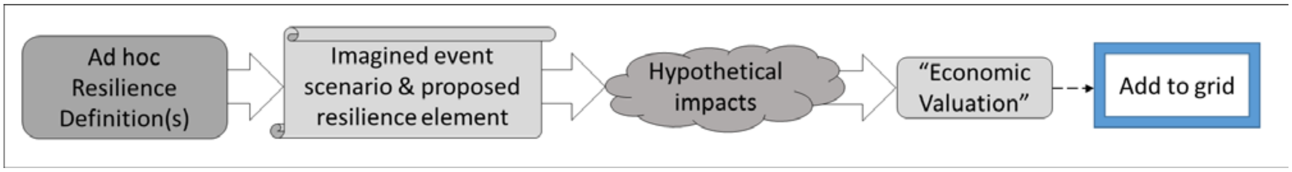


Figure 1. Common Resilience Justification Process

A typical approach is to use one or more of the loosely defined definitions and then to imagine a disruptive event. Hypothetical impacts without and with a proposed resilience improvement are generated and from these and attempt is made to determine an economic valuation, usually based on the supposed avoidance of customer minutes of outage. Very often the choice of resilience element has been pre-determined, and the analysis is intended to provide some form of justification for the expenditure and so these methods are often aimed at considering a specific change, not considering alternatives and tradeoffs. The savings posited in this approach are often not measurable.

The limitations of this approach are due to a basic gap in what should be a strong conceptual foundation for resilience. As illustrated in Figure 2, there should be a relationship between definition and valuation that supports a decision process and that connection should be via a quantification step. The presently missing middle step (quantification) is needed to complete the definition and enable downstream analysis and decision-making.

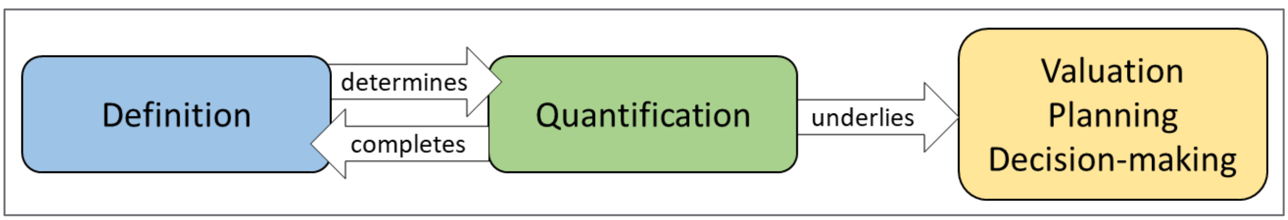


Figure 2. Complete Definition Chain

Unfortunately, no analytically based quantification process or method exists for grid resilience. The ad hoc approaches suffer from several shortcomings:

- Lack of a rigorous, consistent, complete, and comprehensive definition of resilience
- Inability to determine how widely different aspects of resilience can be placed on a common basis for joint mathematical analysis
- Failure to account for structural effects
- Lack of measurability of system resilience behavior or ability to predict behavior exclusive of some specific exogeneous event

Consequently, present methods do not provide a strong basis for evaluating disparate alternatives, even though that is exactly the kind of analysis utilities need. Figure 3 shows a better process model. By introducing a quantification method based on a rigorous resilience definition, we can create a methodology consonant with typical utility planning processes. As shown, the process can use the quantification process to simultaneously evaluate many options and place them on a common basis so that comparison and tradeoff analyses can be done.

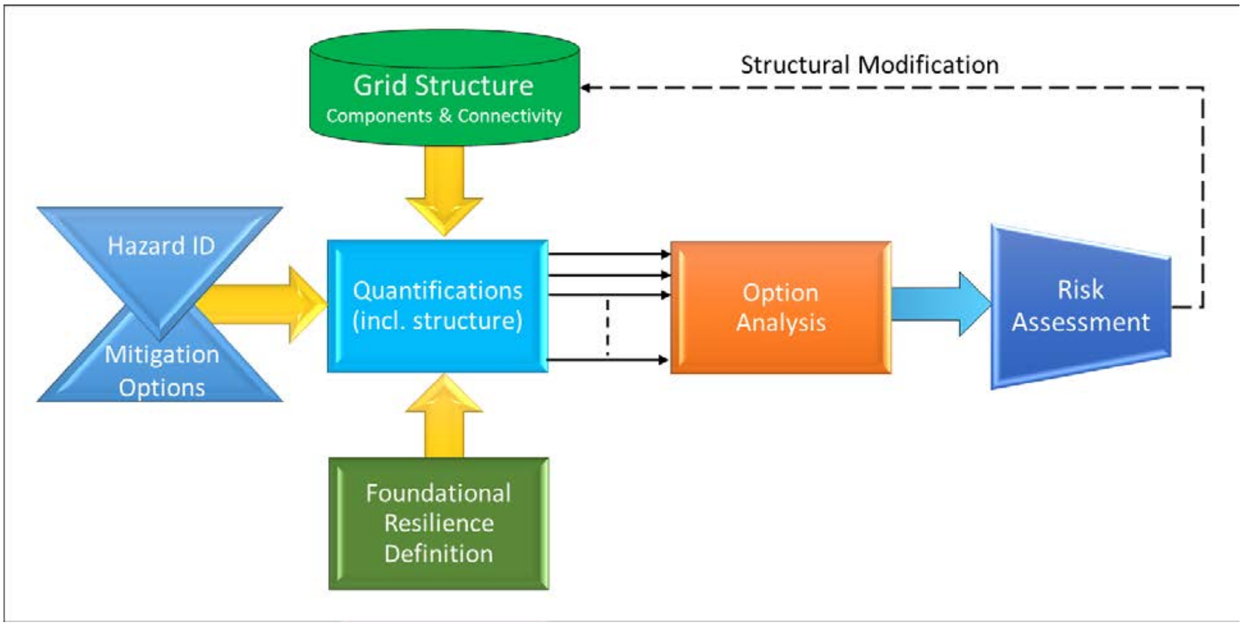


Figure 3. Structural Analytical Resilience Approach

The issue of foundational resilience definition has been addressed in previous work.[1,2] The present document provides a structural analytic method for quantifying grid resilience (or resilience of any system). While the focus and examples here are for electric grids, the method applies equally well to whole energy systems as well as other complex systems like cities. Here we address the Quantifications block in Figure 3; the complete process is beyond the scope of this document.

The quantification method depends on an approach that considers both intrinsic component characteristics and structure. To develop this, we will consider how *reliability* is treated in other (non-electric utility) industries as a conceptual template. Note that we are not going to compute reliability in this method; we will just look to the non-utility reliability calculation methods as conceptual process models for grid resilience quantification.

[1] JD Taft, Electric Grid Resilience and Reliability for Grid Architecture, PNNL-26623, March 2018, available online: https://gridarchitecture.pnnl.gov/media/advanced/Electric_Grid_Resilience_and_Reliability_v4.pdf
[2] S Widergren, et. al, Toward a Practical Theory of Grid Resilience, PNNL-27458, April 2018, available online: https://gridarchitecture.pnnl.gov/media/advanced/Theory_of_Grid_Resilience_final_GMLC.pdf

2.0 Grid Resilience Concepts: Parallels with (Non-Utility) System Reliability

The electric power industry is unique in its approach to reliability, in that its metrics are backwards looking (in time) and conflate system characteristics with external events. The typical definitions for grid resilience are not useful for making architectural decisions and a great gap exists in that there are no methods to quantify grid resilience, and importantly, consider the effect of structure on resilience.

Here we provide an overview of a methodology to quantify resilience in electric power grids and to incorporate structural considerations into that quantification. We will not use the traditional electric utility views of either reliability or resilience to do so.

This diagram in Figure 4 is an illustration of the Grid Architecture definition of grid resilience.

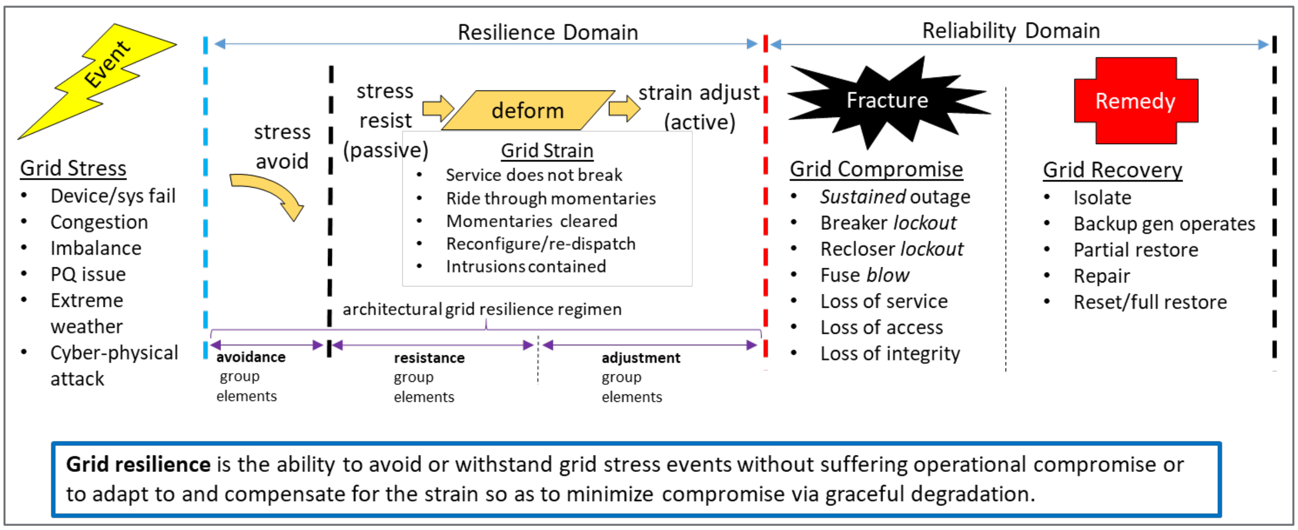


Figure 4. Resilience Defined for Grid Architecture

With this definition in mind, we next consider how reliability is treated in industries such as electronics and aerospace. In those fields, reliability is a forward-looking function of system component intrinsic characteristics and structure. Figure 5 shows the basic approach.

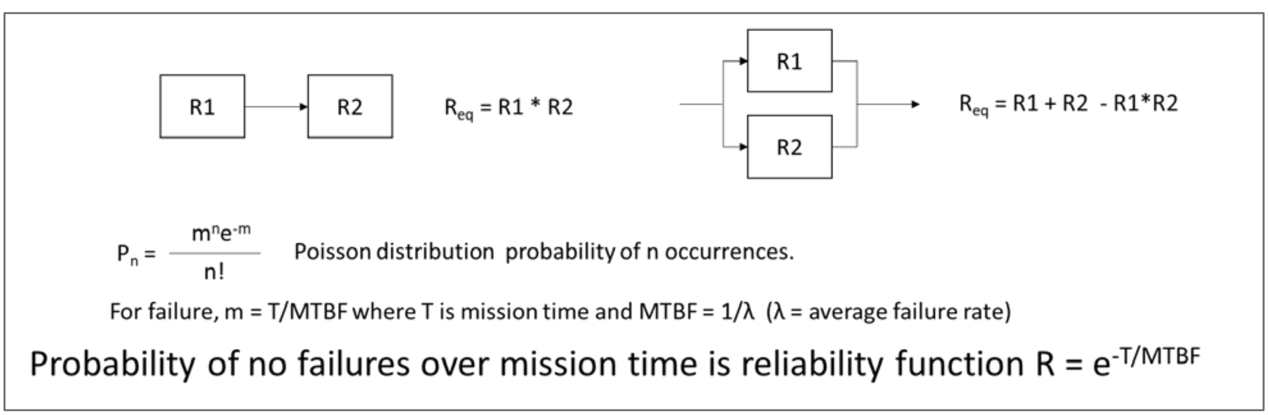


Figure 5. Typical Reliability Analysis Process for Non-Utility systems

Components are characterized in terms of a common property (stress failure rate or its inverse, Mean Time Between Failures or MTBF). Component ratings are combined according to the structure in which they exist in the system, leading to a system level equivalent MTBF. The combination process employs simple algebraic rules that describe how to combine component MTBFs under various structural arrangements. The Poisson Distribution model is invoked to develop a reliability equation that predicts the probability of zero failures over a specific forward-looking mission time. This equation is a function of the system MTBF (and therefore system structure) and the mission time window. Quantifying this allows the engineer to determine which components must be improved or how structure must be changed to meet to the reliability objective. Notice that this method does not depend on hypothesized external events and does explicitly include system structure effects.

Here we take a similar approach for grid resilience (not grid reliability). Components of the grid shall be assigned a parameter that indicates their potential contributions to grid resilience. Algebraic rules show how to combine component quantities according to the grid structure in which they reside. The case of grid resilience is a bit more complicated than the electronics or aerospace reliability cases, but not massively so.

3.0 Basis for Resilience Quantification

We begin with the following postulates:

- Grid resilience is a function of component determinants (resilience-related characteristics), grid structure, specific vulnerability, and a forward time window
- Resilience is only defined for the complete system at a specific Point of View (typically a delivery point or point set)
- Component determinant blocks may be reduced to a single equivalent block within a grid structure

Because of the second postulate, there is no single quantification of resilience for a grid. This is a consequence of the decentralized nature of power grid infrastructure.

The homolog[3] of the component MTBF in reliability theory is the resilience determinant block or d-Block. It has a rating that codifies the potential contribution of a component to grid resilience in the context of a specific vulnerability, time window, and Point of View. To combine d-Block quantities, d-Blocks are connected to form a structure that is determined by (but is not necessarily the same as) the structure of the grid. Figure 6 shows an example d-Block diagram. Every grid has a set of such structures (whether expressed or not). Collectively they represent an eighth structure class.[4]

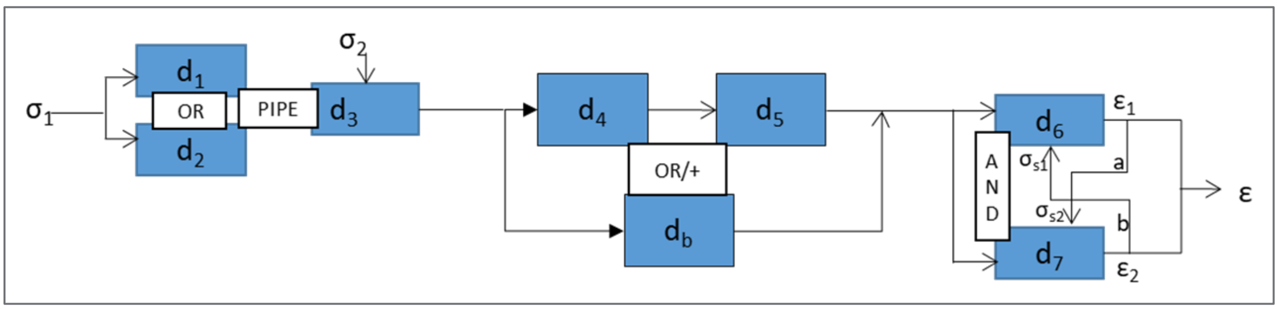


Figure 6. Simple Example d-Block Resilience Structure Diagram

The d-Blocks are grid component abstractions that, when combined through structure, determine the resilience of the grid from a particular PoV. Since d-Block quantities must be combined arithmetically, it is necessary either to make them dimensionless or to put them into the same units. The dimensionless approach is used here and further, the range of quantities is restricted to $0.0 \le d \le 1.0$. Zero implies that the component contributes nothing to resilience; 1.0 is the maximum contribution a component could make.

Note that d-Blocks and d-Block diagrams are multi-scale concepts. A d-Block can represent a single device, a subsystem, or even a whole regional grid. The granularity level at which the abstraction is employed is dependent on the nature of the decision being made and ability to assign a d-Block quantity. If it is not clear how to assign a d-Block quantity, the item in question can be broken down into subsystems and components until d-Block quantities can be assigned,

[3] Homologous: showing a degree of correspondence or similarity.

[4] Grid Architecture defines seven structure classes for the grid: electric infrastructure, industry structure, regulatory structure, information and communication technology (ICT) superstructure, control structure, coordination frameworks, and convergent networks (such as water, natural gas, transportation).

and then the d-Block for the item can be determined by combination of the individual d-Blocks into a single equivalent d-Block.

A d-Block structure can be reduced to a single equivalent d-Block using reduction rules (resilience algebra).

4.0 Resilience Algebra Rules

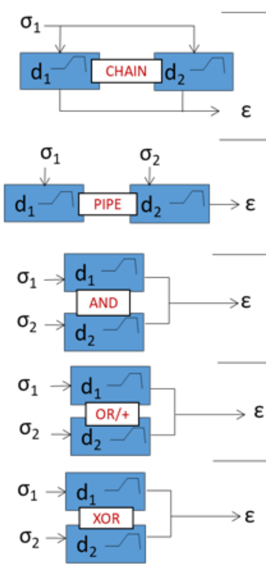
Conceptually, a d-Block is a relationship between a stress and the resultant strain on a grid component. The quantity assigned to the d-Block is a simple multiplicative conversion factor from stress to strain. Conceptually, the inverse of the d-Block quantity, d^{-1}, is homologous with elastic modulus in material science. We shall work with d instead of d^{-1} for convenience, and so write $\varepsilon = d\sigma$, where ε is strain and σ is stress.

We introduce a set of axioms for d-Block reduction in Figure 7.

4.1 Basic Rules

The first row represents a case where several identical components are all subject to the same stress. In the second and third rows, two components are subjected to individual stresses, but both must work for the grid to work. Note that the components may be operate serially (PIPE) or concurrently (AND). It is the dependency on both that matters here. The fourth row is an example of parallel redundancy in that the grid works if one or the other works (or both), hence the OR/+ designation. The last row represents the case where one or the other or the components must work, but not both at the same time (think hot backup), hence the strong disjunction (XOR) designation.

Note that in the first three rows, the combined d quantity is always less than either of the component quantities. This reflects the essential dependency of the components on each other. In the last two rows, the combined quantity is always greater than either of the component quantities, which is an indicator of how to use structure to improve resilience.



Equivalent single block	incr vs. d_1 alone (+/-)	Description
$\delta = \min[d_1, d_2]$ N element case: $\Delta = \min[d_k]; 1 \le k \le N$	$d_1 > d_2$; $-(d_1 - d_2)$ $d_2 > d_1$; 0	chain weakest link case All elements perform same or similar function and are subject to common stress.
$\delta = d_1 \times d_2$ N element case: $\Delta = \Pi[d_k]; 1 \le k \le N$	$-d_1(1-d_2)$	sequential operation case Elements perform different functions in a process or work flow.
$\delta = d_1 \times d_2$ N element case: $\Delta = \Pi[d_k]; 1 \le k \le N$	$-d_1(1-d_2)$	co-dependent operation case Differing elements must work jointly or cooperate.
$\delta = d_1 + d_2 - d_1 \times d_2$ N element case: $1-\Delta = \Pi[1-d_k]; 1 \le k \le N$	$d_2(1 - d_1)$	parallel redundant case Similar elements share a load passively. multiply anti-resiliences
$\delta = \max[d_1, d_2]$ N element case: $\Delta = \max[d_k]; 1 \le k \le N$	$d_1 < d_2$; $d_2 - d_1$ $d_2 < d_1$; 0	One or the other operates, but not both. alternate component case

Figure 7. Basic Reduction Axioms

The first rule is an expression of the saying “a chain is only as strong as the weakest link.” The weakest link sets an upper bound on resilience. However, this model requires that the elements of the chain be identical in function and that all see the same stress, which is not common in real systems.

The second and third rules are simple dependencies: both must resist stresses; if either fails then the combination fails. The formulation follows the system reliability cascaded-blocks model.

The fourth case comes from considering that anti-resiliences[5] in parallel multiply, so the solution derives from a formulation following the system reliability parallel blocks model:

$$1-\delta = (1-d_1)\,(1-d_2)$$

The last rule is an expression of how the strongest of exclusive alternative elements sets a lower bound on resilience.

4.2 Compound Reductions

These basic rules may be used to reduce more complex structures, as Figure 8 shows.

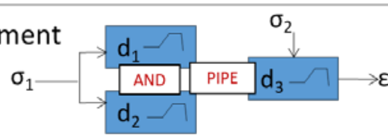
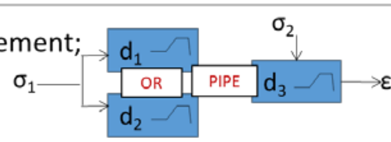
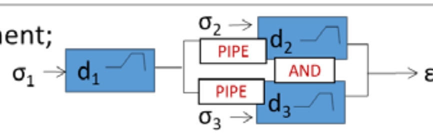
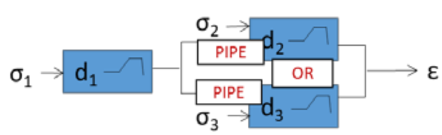
1. Common downstream element (all must work) AND/PIPE connection 	$\delta = d_1 \times d_2 \times d_3$
2. Common downstream element; OR/PIPE connection 	$\delta = (d_1 + d_2 - d_1 \times d_2) \times d_3$
3. Common upstream element; PIPE/AND connection 	$\delta = d_1 \times d_2 \times d_3$
4. Common upstream element; PIPE/OR connection 	$\delta = d_1 \times (d_2 + d_3 - d_2 \times d_3)$

Figure 8. Compound Reductions

4.3 Cross Coupling

A more complex case arises when the strain that develops in one component as a result of stress causes stress on another component. Consider for example, a case where wind stress on a utility pole causes it to start leaning (strain), thus adding stress to a neighboring pole through the attached wires. The effect can be a unilateral (single-coupled) or bilateral (cross-

[5] Anti-resilience = 1 – resilience. See the d-Block assignment section below for more on how d-Block parameters are determined.

coupled). Figure 9 provides the reduction rules for single-coupled and cross-coupled cases. In these cases, it is necessary for the engineer to estimate the coupling coefficient(s).

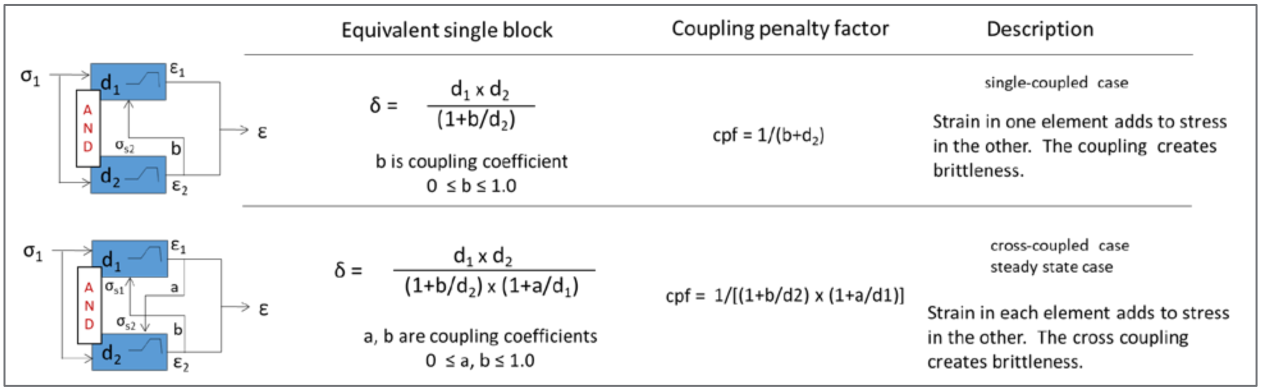


Figure 9. Reduction Rules for Cross Coupling Effects

The single coupled case derives from considering that strain exhibited by d_2 becomes additional stress input to d_1 via coupling coefficient b. We may then write

$$\varepsilon_1 = \sigma/d_1 + b\sigma/d_2 \times 1/d_1$$

and solve for ε_1/σ to find a new equivalent for d_1 that accounts for the interaction with d_2. The cross coupled steady state case is solved in a similar (if slightly more complicated) fashion involving a pair of simultaneous equations.

4.4 Shifting Pick Points

Adding a component in parallel to an existing pair of components to improve resilience by adding redundancy can be done in three ways. Figure 10 shows a comparison of the approaches and is an example of how structure affects the degree to which adding a component can contribute to resilience. Not all structures are equal when it comes to resilience.

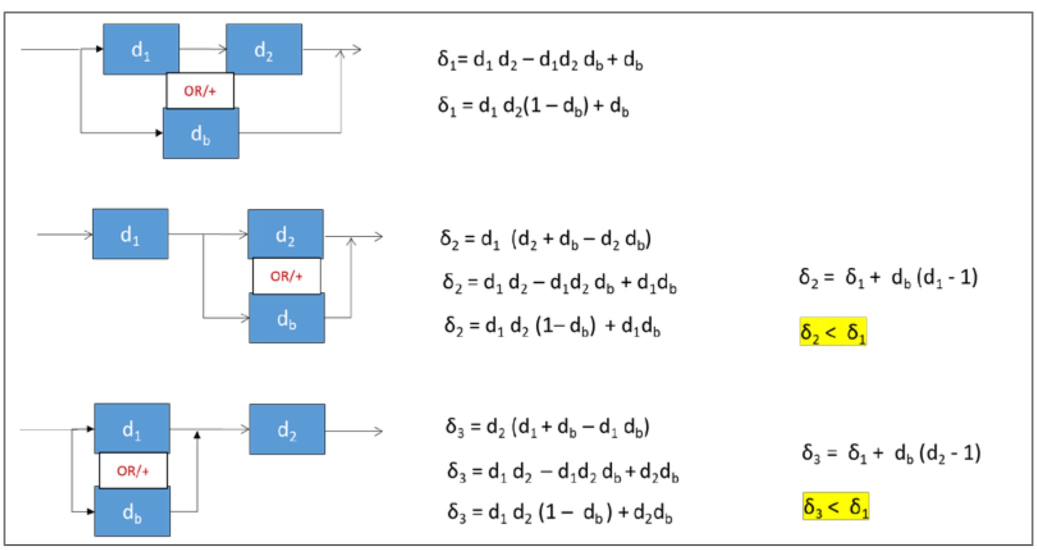
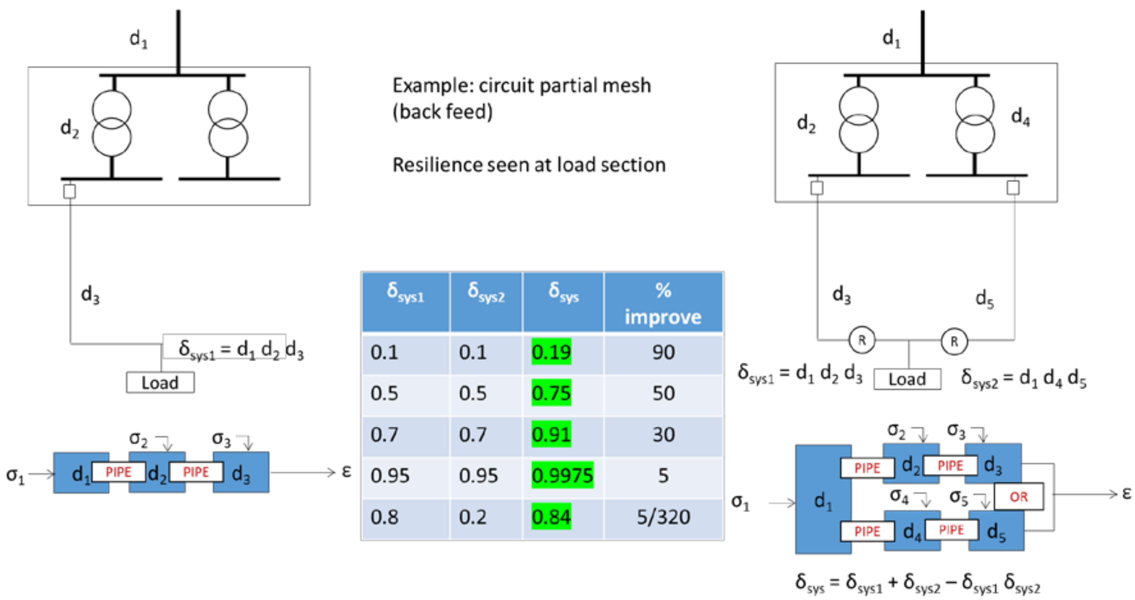


Figure 10. Reduction Rules for Pick Point Shifting

5.0 Applying Resilience Algebra

Given the basic set of reduction rules and ordinary algebra, we may apply this approach to evaluation of some common grid alternatives.

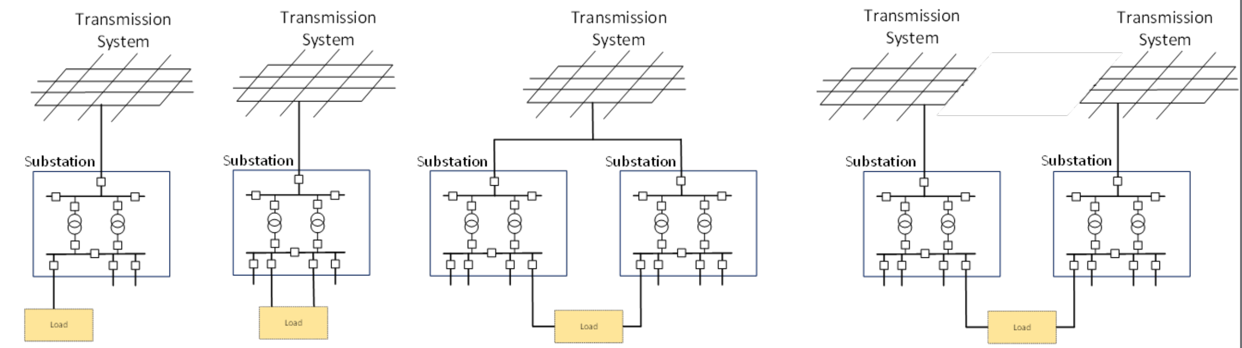
Redundant circuit paths: comparison of single feeder with two feeder-backfeed arrangement shown in Figure 11 shows how this structure can improve resilience or alternately how much a single feeder must be improved to provide equivalent resilience to the backfeed arrangement.



δ_{sys1}	δ_{sys2}	δ_{sys}	% improve
0.1	0.1	0.19	90
0.5	0.5	0.75	50
0.7	0.7	0.91	30
0.95	0.95	0.9975	5
0.8	0.2	0.84	5/320

Figure 11. Feeder Backfeed Resilience Comparison

The same concept can be applied on a larger scale, as shown in Figure 12. The analysis shows how increasing separation of the sources has a monotonic but diminishing returns effect on resilience. In the three right hand cases, the sources are progressively separated at larger scales, as compared to the singe feed base case on the left. While resilience always increases moving to the right, the increases diminish in size (most likely the costs increase in size). The resilience quantification enables an analytical tradeoff decision on where to apply the redundant structure.



$\delta = d_1 d_2 d_3$ | $\delta = d_1 d_2[2d_3 - d_3^2]$ | $\delta = d_1 d_2[2d_3 - d_2 d_3^2]$ | $\delta = d_1 d_2[2d_3 - d_1 d_2 d_3^2]$

Transmission $d_1 = 0.9$; Substation $d_2 = 0.7$; Feeder $d_3 = 0.5$

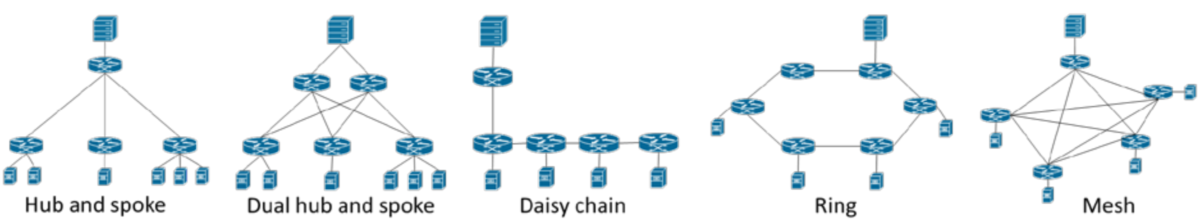
$\delta = 0.32$ baseline	$\delta = 0.47$ 47% over base	$\delta = 0.52$ 63% over base	$\delta = 0.53$ 66% over base

Transmission $d_1 = 0.7$; Substation $d_2 = 0.7$; Feeder $d_3 = 0.5$

$\delta = 0.25$ baseline	$\delta = 0.37$ 48% over base	$\delta = 0.40$ 60% over base	$\delta = 0.43$ 72% over base

Figure 12. Effect on Resilience of Separating Sources at Differing Scales

Communication topologies may also be modeled and analyzed using this method. A wide array of communication network topologies is available; Figure 13 illustrates the resilience analysis of several such topologies.



Network type (all d_i =0.8)	Paths	Path length	$\delta_{network}$
Hub and spoke (base case)	1	3	0.512
Dual hub and spoke	2	3	0.762
Daisy chain	1	3-9	0.512 (3) to 0.134 (9)
Ring	2	(3,11), (4,8), (7,7)	0.554, 0.509, 0.375
Mesh	6	(3, 5, 5, 6, 7, 9), (3, 5, 5, 6, 6, 7)	0.889, 0.905

1 path chain: $\delta_{network} = \Pi[d_j]$; $1 \le j \le M$

N path case: $\delta_{network} = 1 - \Pi[1-d_{chain\ k}]$; $1 \le k \le N$

Figure 13. Resilience Analysis of Typical Communication Topologies

This method may even be applied to very general structures such as classic centralized, decentralized, and distributed systems. Figure 14 illustrates the resilience superiority of distributed architectures but note that decentralized structures may have less functionality than centralized ones due to isolation and so additional factors may influence structure choice.

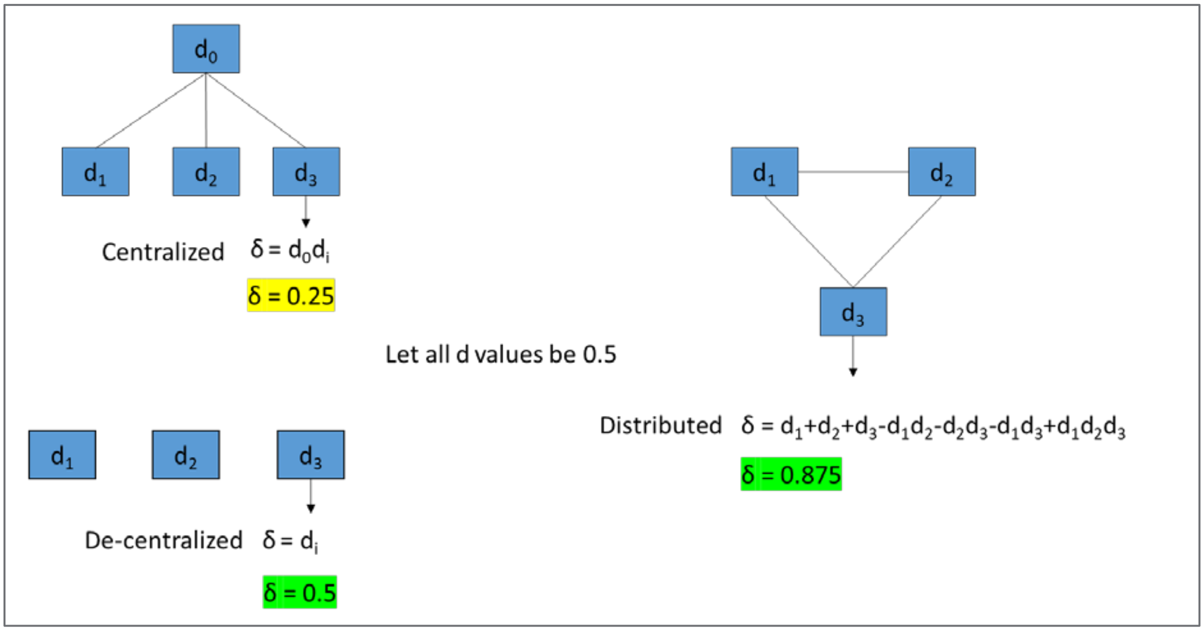


Figure 14. Simple Resilience Analysis of Common System Structures

This last example shows how the method can be applied at very high levels (i.e. low detail granularity) to provide results that guide architecture decisions without even needing to have much information about the systems in the early stages of the architecture work. These can be encapsulated into general architectural principles regarding the choice of centralized, de-centralized, and distributed grid structures.

5.1 Microgrids

Microgrids are often considered in the context of improving grid resilience. Resilience algebra can be employed to analyze microgrids and in the process reveals what it is about microgrids that can improve resilience. Figure 15 shows a simple microgrid configuration. It is clear from the analysis that the existence of an alternate energy source and delivery path are the key elements that contribute to resilience gain and therefore it is possible to obtain the same gain with other structures containing the same elements.

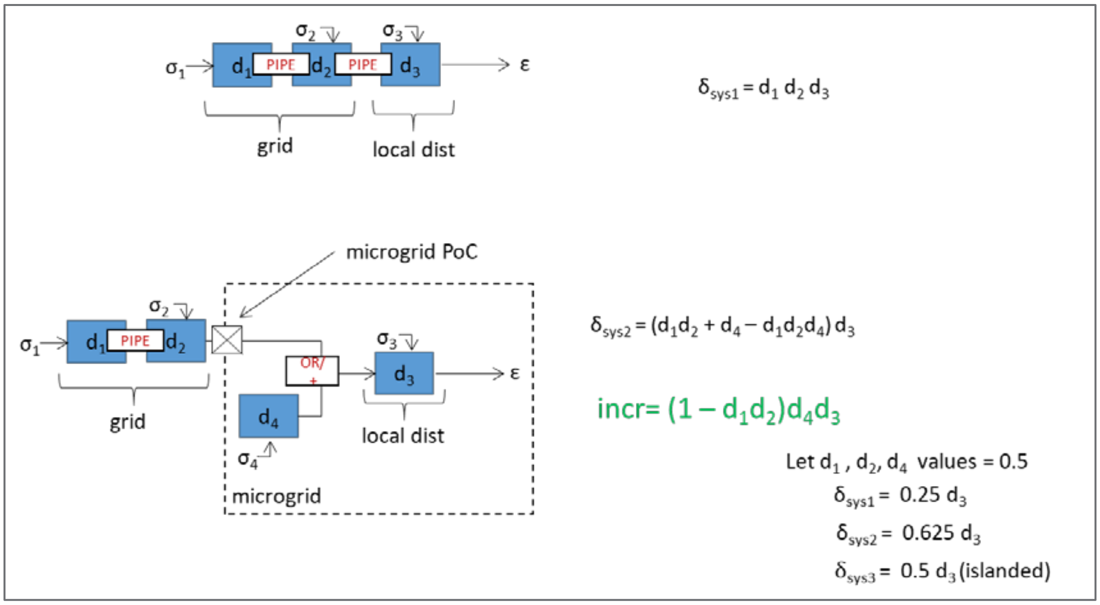


Figure 15. Simple Microgrid Resilience Analysis

Microgrids may be connected in various configurations to create microgrid networks. For example, Figure 16 shows a pair of microgrids chain-connected so that power may wheel downstream.

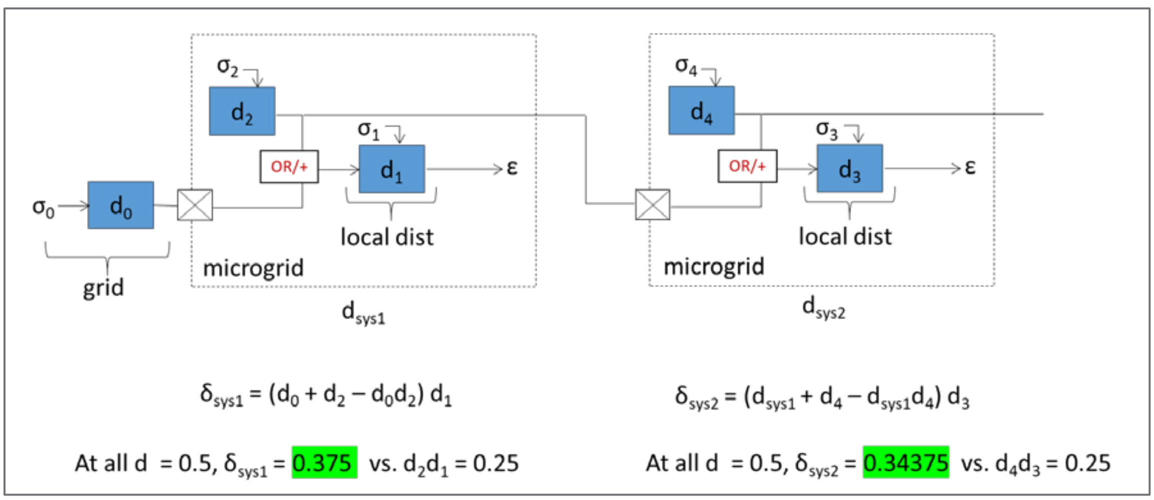


Figure 16. Chained Microgrids (Wheeling Case)

Alternatively, microgrids may be cross-connected in pairs, as shown in Figure 17, in order to support each other.

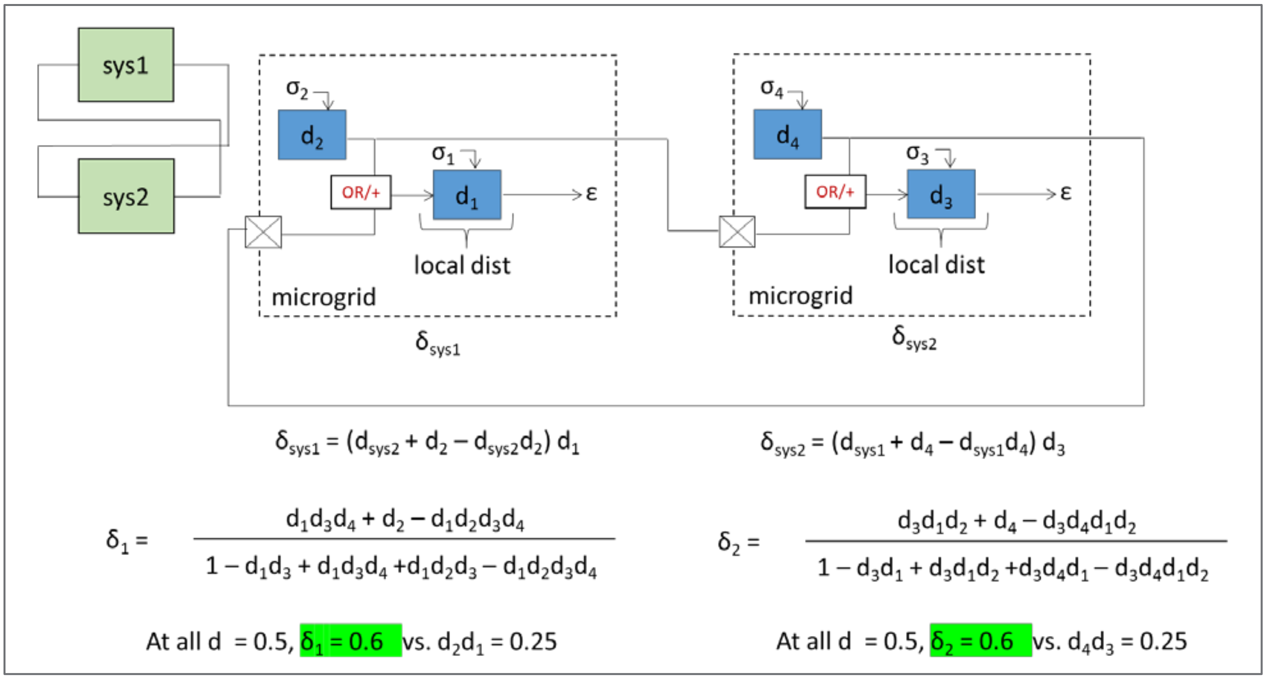


Figure 17. Cross-Connected Microgrids

The cross-connection model may be generalized to an arbitrary number of microgrids connected in a loop. Figure 18 shows such an arrangement and indicates that a general set of matrix equations may be solved simultaneously for the equivalent resilience.

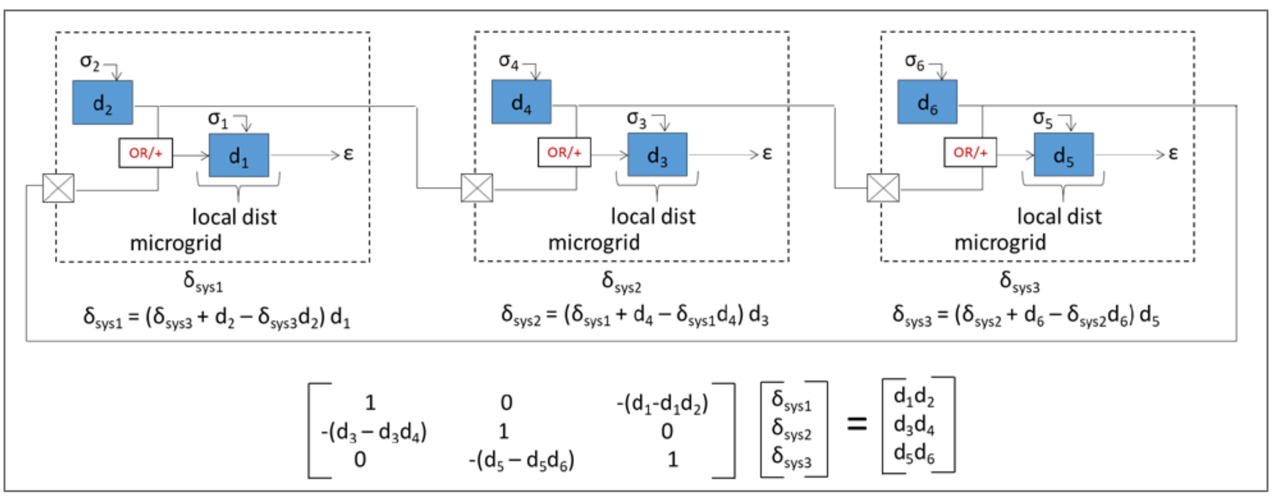


Figure 18. General Microgrid Loop Model

A recent popular structure for microgrid networks is the nested microgrid, as shown in Figure 19.

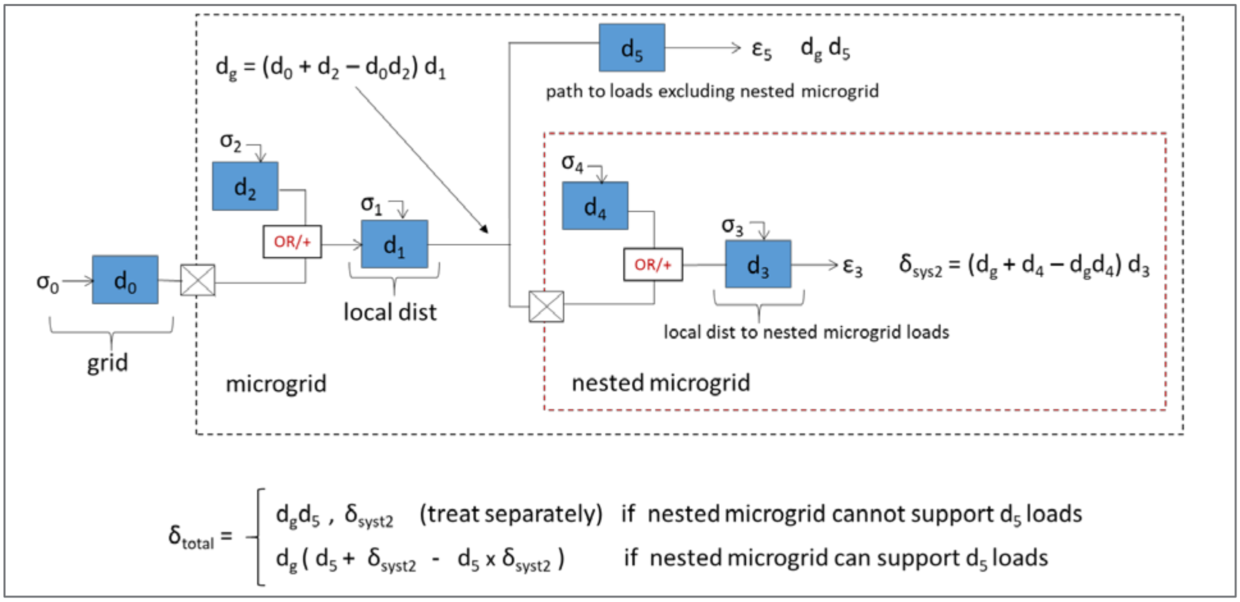


Figure 19. Nested Microgrids

Microgrids may connected in as many different topologies as communication network elements, so the ability to apply the resilience algebra principles is needed to handle new configurations. One caution about microgrids: it is usually necessary to solve for both islanded and non-islanded cases and to be clear about what loads each microgrid can support, both inside and outside of the microgrid.

5.2 Buffers

Volatility is fundamentally different from other stresses because it can propagate through the system and affect all components and whole system performance as seen at a point of delivery. The essential value of grid sale storage is that it can act as a buffer, and thereby decouple volatilities.[6] Volatility may arise from a variety of sources, some transmission-connected, some distribution-connected and the volatility may be exported in either direction across the Transmission/Distribution interface, or laterally at either level, to the detriment of system performance. Embedded storage can provide the buffering that has been missing from power grids that will absorb the shock of power flow volatilities. From an architectural perspective, buffering may be applied throughout the grid, but from a practical standpoint, it will be deployed in multiple ways. From a resilience structure standpoint, there are several models, starting with the simple one-port structures in Figure 20. Note that regardless of whether the buffer is attached between volatility source (such as stochastic generation) and grid or between grid and passive load, the resultant equivalent resilience contribution is the same.

[6] R O'Neill, 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 .

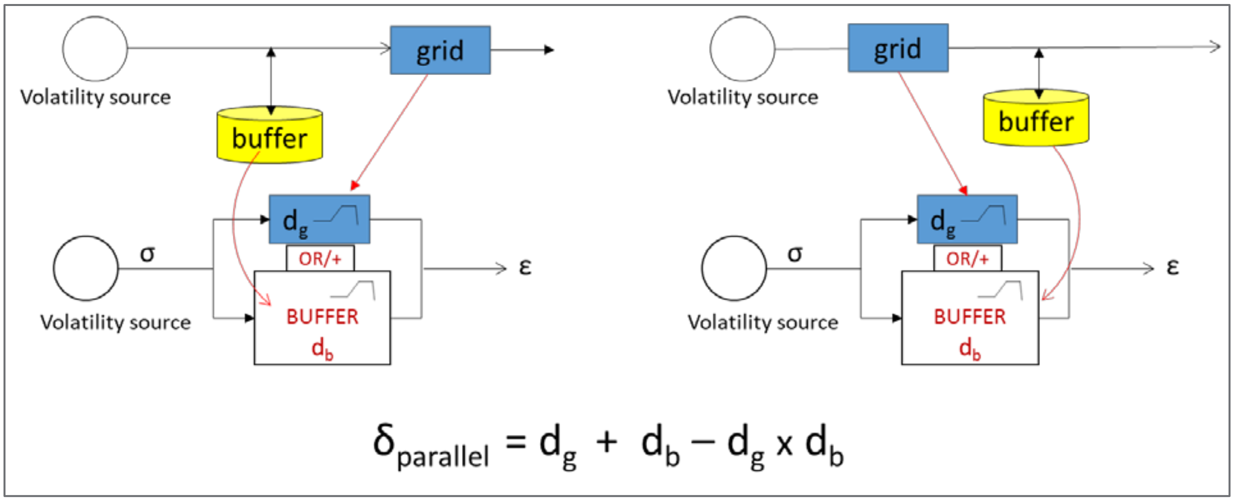


Figure 20. Two Single-Port Storage Parallel Buffer Models

Figure 21 illustrates a more complex model in which volatility is exported from transmission into distribution, but also arises from distribution-connected generation and active apparent loads (such as loads with behind-the-meter solar PV).

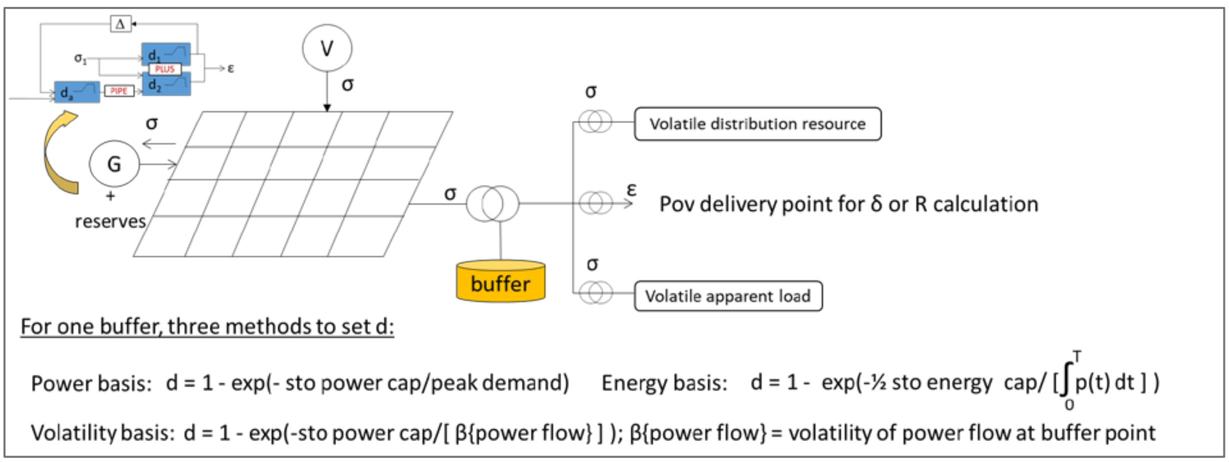


Figure 21. Storage as Core Infrastructure for Volatility Decoupling

When determining the d-Block value for buffers in such situations, it is necessary to make a choice regarding buffer operating mode and resultant stress model. Three typical approaches are shown in the figure: power basis, energy basis and power flow volatility basis. For the volatility basis, β may be computed in terms of absolute power flow variance, or may be computed in terms of the variance of the difference between actual power flow and nominal or expected demand, the latter allowing for smaller size buffers, assuming the appropriate buffer controls.

Once the buffer operating mode is defined, the relationship of system δ to the grid and buffer d-Block values is a straightforward application of the OR/+ reduction rule.

When considering a network of coordinated buffers, such as illustrated in Figure 22, the general n-element version of the OR/+ rule applies to the *buffer system*, and then the OR/+ rule may then be applied to the combination of *buffer system* and grid.

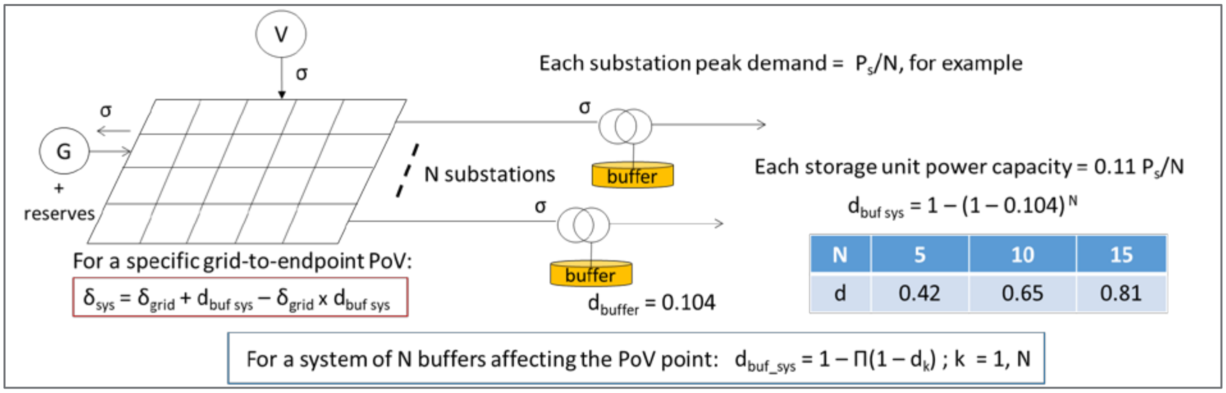


Figure 22. Coordinated Storage Networks as Core Infrastructure

The use of a network of buffers allows each individual buffer to be small, while the combined effect can be large. There is a diminishing returns effect in play however, so that increasing the number of buffers without limit eventually does not make sense. In addition, remember that the storage network buffers must be controlled jointly, and so trying to use a very large number of very small behind-the-meter storage units will run into other practical coordination and control issues so that such arrangements may lose their functional effectiveness.

6.0 Assigning d-Block Quantities

It should be clear by this point that assignment of d-Block quantities can be a crucial aspect of this methodology. We say “can be” because for some decisions, the algebraic analysis can provide useful directional decision results without even having the actual d-Block quantities. However, for specific tradeoff analyses, the d-Block quantities are needed.

6.1 Template for d-Blocks

The ratings for d-Blocks are determined by the intrinsic characteristics of components with reference to specific stresses. Consequently, it is necessary to know which stress or stresses are under consideration. Once that is determined, a template for calculating d-Block quantities from component characteristics may be applied. Figure 23 shows two template forms that guarantee the constraints on d-Block quantities will be met. The d-Block functions are designed to be twice-differentiable and concave, so that they rise from zero and asymptotically approach unity. This form inherently encapsulates a diminishing returns effect.

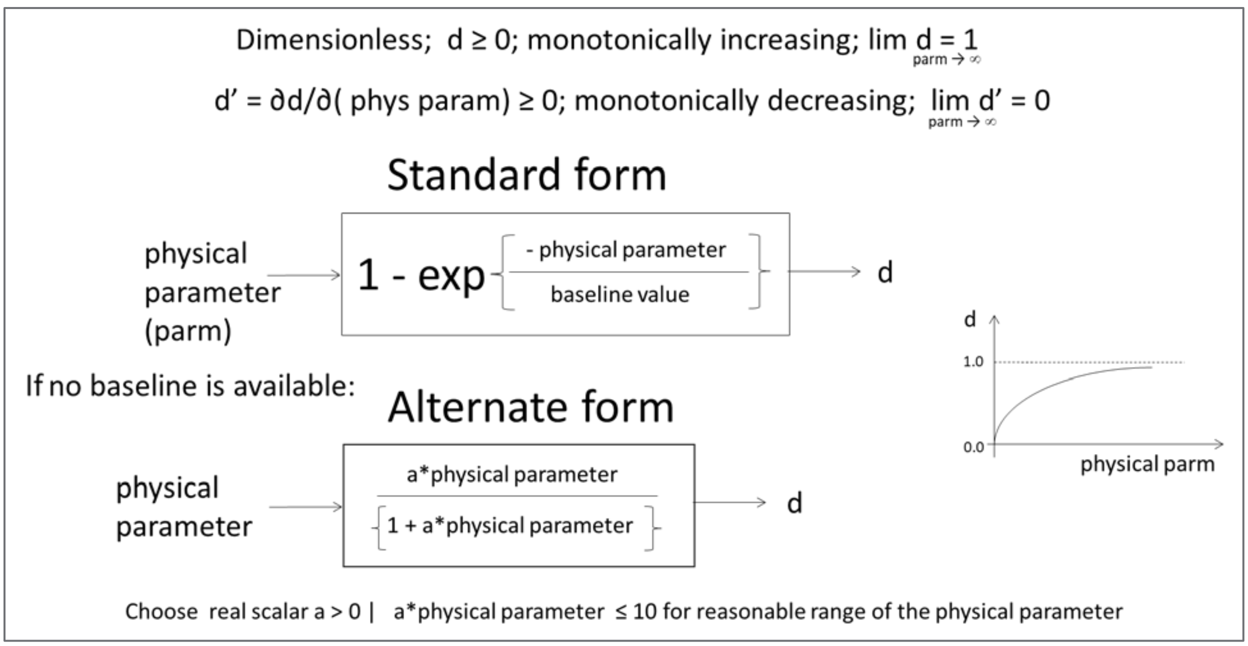


Figure 23. d-Block Quantity Assignment Templates

As examples, for stress avoidance, d may be calculated as:

d = 1 – exp[-(elements removed from exposure)/(total elements)].

For resistance (hardness), say for a transformer that is subject to overload:

d = 1-exp(-max rated loading/nominal rating).

or a Grade B wood pole loading:

d = 1-exp(-overload withstand factor).

or a transformer top oil temperature withstand:

d = 1-exp(-max rated emergency temp/nominal operating temp).

For adjustment (shock absorbance), say for a voltage regulator,

d = 1-exp[-0.5(voltage BW/β{voltage})]; β{voltage}) = voltage volatility,

or for regulating system frequency via AGC:

d = 1-exp[-0.5(up-down regulation capacity/β{load})]; β{load} = apparent load volatility.

In the last two examples, regulation must handle up and down cases. Therefore a 0.5 factor appears in the expression (nominally, half of the available band is available in each direction). See Figure 24.

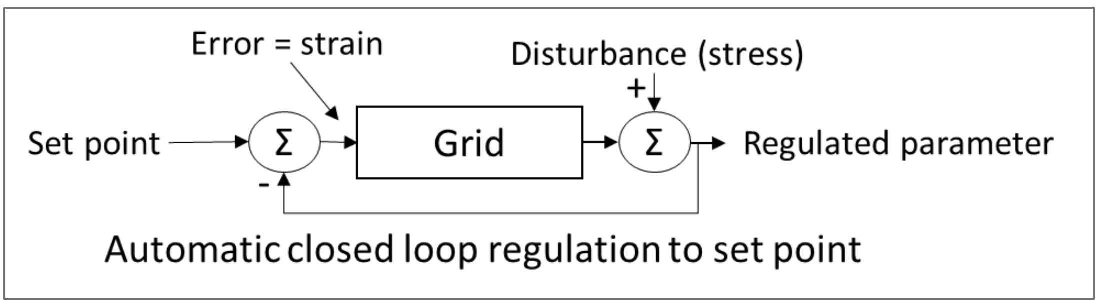


Figure 24. Stress and Strain in a Closed Loop Control

6.2 The Resilience Function

The actual Resilience function is calculated from the equivalent d quantity (δ in the examples) as shown in Figure 25.

Poisson Distribution	$P_n = m^n e^{-m}/n!$	Let interval rate m = rt, r = rate, t = time
Then,	$P_n = (rt)^n e^{-rt}/n!$	Let r = breakage event per period = (1-δ)/T
Then, for n = 0 breakages,	$P_0 = e^{[-t(1-\delta)/T]}$	Probability of zero breakages over time t

Resilience function: $R = e^{[-t(1-\delta)/T]}$

t = time
T = resilience time horizon period
δ = path equivalent d-Block quantity

Figure 25. Resilience Function Calculation

Note however that R is monotonic with δ, so it is not actually necessary to calculate R, since decisions and comparisons can be made directly based on the δ quantities. Figure 26 illustrates the overall resilience quantification process.

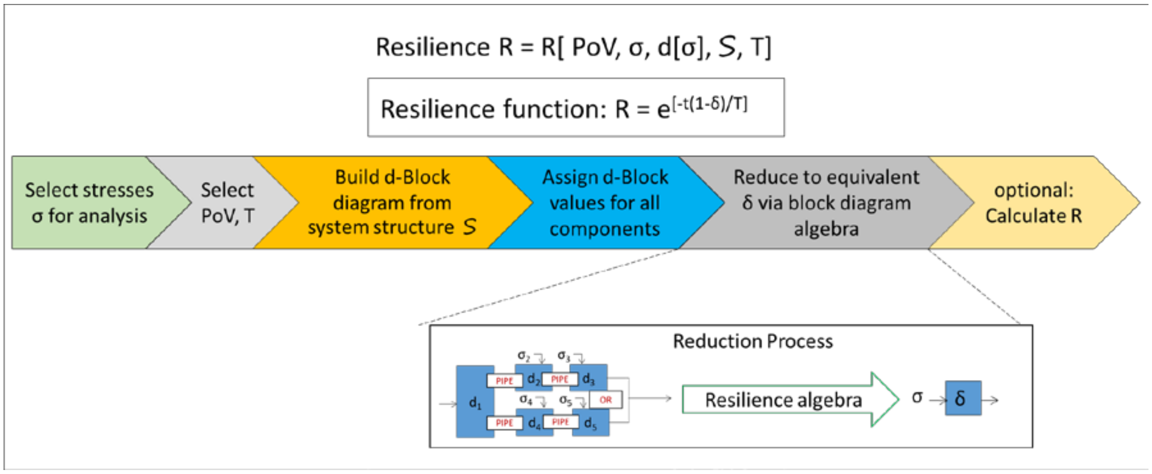


Figure 26. Resilience Quantification Process Overview

7.0 Final Comments

By defining grid resilience in terms of a stress-strain model, it is possible to develop an analytical approach to quantifying the contribution of various components to grid resilience as seen at a delivery point or point set. In addition, the effects of grid structure can be considered by representing grid resilience as a structure itself and using an approach modeled after the reliability treatment used in electronics and aerospace. This leads to a *resilience algebra*, a set of reduction rules and relatively simple algebraic methods that facilitate converting a complicated resilience diagram into a single equivalent block, which facilitates option decisions in the context of grid resilience.

Some key points about this approach:

- Grid resilience is affected by both component characteristics and system structure
- Resilience can be modeled in terms of resilience determinants arranged in a block diagram that reflects system (grid) dependencies and structural influences
- Component resilience determinants derive from the stress responses of components; these come from *intrinsic characteristics* of the components, not external events and consequences; hence there is no reference to hypothetical catastrophic externalities
- Resilience block diagrams can be reduced to a single equivalent quantity, using reduction rules and resilience algebra
- By specifying the set of stresses to be considered and assigning the d-Block values of the components appropriately, a very wide range of stress types can be considered, meaning that the method is not limited to storm damage or attack, but can be applied to situations as varied as poor operator training and faulty software upgrades too.

While this approach to resilience quantification is robust and broadly applicable (and not just to grids), it is not sufficient in itself to resolve grid resilience issues. It must be integrated into a planning methodology that identifies vulnerabilities and mitigation options and provides the option and risk analyses that yield decisions on how to modify electric power systems to achieve resilience goals. Structural analytic resilience quantification provides the resilience quantification step in Figure 3; the other steps are the crucial elements of a complete process that can make use of the quantification methodology described here.

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