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Towards a More Resilient Microgrid during Extreme Events - A Case Study of Hurricane Ike 2008

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ABSTRACT

The main objective of power system grids is to make electricity accessible. Environmental disasters, which can contribute to power outages with short- or long-term consequences, have consistently jeopardized the mission. In these extreme situations, there is a loss of revenue and electrical supply, and the electricity grid needs to be repaired after the ensuing pandemonium. Therefore, it is explored as a subject of attention in the contemporary power systems. This research offered a thorough microgrid modeling technique that improves the resilience of the power system in the region of the V-shaped resilience curve. It manages the microgrid's regulation strategy by examining the microgrid's time-dependent resilience index. The initial strategy was implemented in order to assess its effects on the 2008 Hurricane Ike instance in the Texas city of Matagorda.

KEYWORDS

Energy storage
Islanding
Microgrids
Natural disasters
Resilience

1. INTRODUCTION

In recent years, the impact of natural disasters on power system infrastructure has been a growing concern. These disasters include hurricanes, blizzards, tornadoes, and volcanoes (Gholami *et al.*, 2016). For instance, Hurricane Sandy that occurred in the North-East United States in 2012, destroyed over 10,000 wires, while seven million people were disconnected from the grid (Farzin *et al.*, 2016). The consequences of information technology and power systems, along with the 2010 earthquakes in Chile and 2011 in Japan, were addressed in Kwasinski (2011), Dueñas-Osorio and Kwasinski (2012) and TCLEE Report (2012). Recently, total black-out was experienced in Puerto Rico due to Hurricane Maria, while Hurricane Irma left about 6.5 million Floridians without power (www.theguardian.com, 2017 and www.vox.com, 2017). This loss of service threatens energy power delivery, while the costs associated with downtimes cannot be under-estimated. Hence, there is a need for adequate power system resilience to address this lack of service (Gholami *et al.*, 2016). Figure 1 shows the damage to some of the electricity infrastructure during the 2017 Hurricane Maria.

Figure 1: Damage site during the 2017 Hurricane Maria Event in Puerto Rico

Crawford Holling (Holling, 1973) originally well explained resilience in 1973 as a degree of "the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables."

The implications of natural hazards on the safety, efficiency, and quality of power grids are deemed quite significant, hence, the need to analyze the power systems resilience. Recently the issue has attracted interest across both the study and the national strategy. As per the U.S. Directive 21 on Presidential Policy (PPD-21), (U.S. Presidential Policy Directive 21, 2017), "resilience" means "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions such as deliberate attacks, accidents, or naturally occurring threats or incidents". Throughout the sense of power grids, resilience may be partially designed as a structure of the recovery speed of electricity grid resources following a significant negative situation. Microgrids, energy storage, and renewable energy sources are components that have been designed to improve power system resilience. However, a robust control method, using a state control has been introduced in this work to improve the resilience of power systems within the afore-mentioned components.

Resilience, in some other words, can be the ability of an item or system to regain its former strength and return to the original state after undergoing deformation or stress. The power system is then said to have failed when a part of the load or all the load is not receiving power (simply termed as downtime). This is one of the basic reasons why microgrids have been applied to improving power system resilience (Wang and Wang, 2015; Kwasinski *et al.*, 2012; Kwasinski, 2010; Panteli *et al.*, 2016; and Mukherjee *et al.*, 2014), since they could serve critical loads during an adverse weather impact and improve resilience in an "intentional" islanded mode to prevent failures cascading from conventional grids that could result in a blackout scenario.

Resilience encompasses only one breakdown and repair process, while accessibility encompasses an unlimited number of these processes. This is analogous to that of availability (Kwasinski, 2016). Additionally, resilience means responding to a high anticipatory effect, being willing to return rapidly to its pre-disturbance condition, and studying the case for avoidance or preventing potential recurrence. The adjustment method is similar to the overall feedback control device principle in which the system performance signal is detected and then used to change system variables to accomplish a particular objective.

In Farzin *et al.* (2016), an improvement of power systems resilience, through hierarchical outage management, was proposed using a predictive control-based algorithm. This strategy regarded the whole smart grid as a multi-microgrid system with a decentralized optimization process and control.

Resilience-constrained Unit Commitment (RCUC) strategy, suggested in Eskandarpour (2016), solves concerns regarding resiliency, which are not covered in the Security-constrained Unit Commitment (SCUC) most power utilities depend on RCUC. In

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Buque and Chowdhury (2016), usage of distributed generations (DGs) and microgrids (MGs) to boost power grid stability, concentrating on Sub-Saharan Africa, was reviewed. The use of state controllers has been introduced in this paper to address these challenges by determining the present states of the system and mapping them to a defined resilience metric. In this way, the controller can efficiently manage the microgrid system energy supply and then coordinate it to reduce system downtimes. State controllers have been used in several different applications, such as the robotics system (La-Manna, 2015), in transportation systems such as spacecraft attitude (Li *et al.*, 2016) and metro-trains (Iannuzzi and Tricoli, 2016). State controllers allow to dynamically update the policy at run-time and hence achieves a resilience index beyond the present state.

Control theory was proposed in Bie *et al.* (2017) and Yodo *et al.* (2017) by enabling resilience of complex engineering systems, but short of verified facts that express the association concerning the resilience metric and control. Since resilience is multidimensional, this approach has not been able to quantify resilience. However, this paper presents an increased resilience by quantifying the system metrics using a state controller. It also shows how, during the disruption time, the controller manages the device. It is, therefore, necessary to appeal to an operational resilience referring to "intelligent" control-based measures undertaken to ensure the infrastructure with the capacity and tools to efficiently endure threats as they grow (Panteli and Mancarella, 2015). The major contribution of this research exists in the microgrid regulation centered on quantitative resilience indicators.

2. METHODOLOGY

The microgrid, storage, and clean energy interconnection outlets, which is one of the current designs for improving resilience, is not adequate to endure the perturbations arising from natural catastrophic events. This work, therefore, suggests a new state regulating technique that improves the resilience of the power system by using state parameters. Equation (1) can be used to determine resilience for a specific load when it is assumed that a microgrid has batteries as a type of storage (Kwasinski, 2015).

$$\rho_L = 1 - \left(1 - \rho_B\right) e^{-\mu T_{bank}} \tag{1}$$

where ρ_L and ρ_B are the local resilience and base resilience, respectively, μ is the inverse of power supply downtime ($T_{.D}$), and T_{bank} is the storage capacity. Base resilience is calculated based on Equation (2) given as:

$$\rho_B = \frac{T_U}{T_U + T_D} \tag{2}$$

where T_U is the load time from the power supply. For N number of loads, the resilience is calculated by Equation (3) given as:

$$\rho_B = \frac{\sum_{i=1}^{N} T_{U,i}}{\sum_{i=1}^{N}\left(T_{U,i} + T_{D,i}\right)} \tag{3}$$

Within this study, however, a non-linear State controller was introduced to improve flexibility and adaptability by rising downtime correlated with a V-shaped area. It estimates a triangular form found while measuring the resilience parameter over time. The V-shaped represents the nature of the resilience curve derived from the power system's deterioration and reconstruction phases.

2.1. Proposed State Controller

The operation of the power system is affected by natural disasters, which cause the system to detach itself from its operational stage. The state regulator examines the system parameters in order to modify them to a given fixed point, calculates the system condition, compares it to a list of system specifications, and then feeds this information into the Microgrid Energy Management System (MEMS). The energy storage devices are then enabled by MEMS, supporting the microgrid while opposing disruptions that can arise during natural disasters.

The bus voltage and frequency give the condition of an ac microgrid network. The state control behavior can be described in scientific equations as follows:

$$\Delta x_i = x_i - x; \qquad i = 1,\ 2,\ \ldots,\ N \tag{4}$$

$$\overset{\square}{x}_i = k_p \Delta x_i + k_i \int_0^Z \Delta x_i dt + k_d \frac{d\Delta x_i}{dt} \tag{5}$$

$$\overset{\square}{x}_i - x \rightarrow 0 \ \ \text{(during and after the event)} \tag{6}$$

where
N is the number of state projections
x is the state of comparison
x_i is the approximate state
x_i is the control's performance state.
The proportion, integral, and differential gains are k_P, k_I, and k_d, individually.

The equation output (5) is utilized to transmit a signal to the control and MEMS, which further responds to the regulated energy storage systems at a suitable level by either delivering or consuming real power. The detection error, defined merely as the control code, is programmed to be near zero at any moment, t. In Figure 2, the hierarchical management design is seen. Resilience is time-dependent and, therefore, can be strengthened by minimizing the V-shaped region in Figure 2. The V-shaped area is equivalent to the t_1 to t_2. t_1 is defined as the pre-event condition before time, and t_2 is classified as the post-restorative condition after time. The state of deterioration, which depends on the system's ability to withstand the severe event between t_1 and t_2.

Strengthening this region's resilience is critical and can be accomplished by integrating infrastructure and operation resilience. The critical area of all the transitions is the period during t_1 to t_2, identified as the state of rehabilitation or reconstruction. This condition reflects a more significant proportion of the equipment downtime that can be ameliorated by operation resilience. Stronger resilience (lesser downtime) could be accomplished by moving the entire portion of the curve when $t > t_2$ to the right of t_2 as well as by moving the segment when $t < t_1$ to the left of t_2 and by adding a strong state control as suggested in this work.

In terms of control architecture, the V-shape region can be described as an "energy" element, described as given by Equation (7):

$$V \approx \frac{1}{2}\delta\square t \tag{7}$$

where δ is the resilience inertia showing the reflex behavior of natural hazards on the power grid and where t is the time vector when calculating the resilience values. If evaluating energy storage as a reserve that would be used to boost resilience, we should presume a Battery Energy Storage Device (BESS) that provides autonomous power to the load, T_{bank}.

$$V \approx \frac{1}{2}\delta_{av} T_{bank} \tag{8}$$

where the momentum of average (moving) resilience is provided as:

$$\delta_{av} = \int_t^{t+\delta t} \left|\delta\right| dt \tag{9}$$

Combining Equations (1) and (9) then becomes:

$$V \approx -\frac{1}{2\mu}\delta_{av}\ln\left(\frac{1-\rho_L}{1-\rho_B}\right) \tag{10}$$

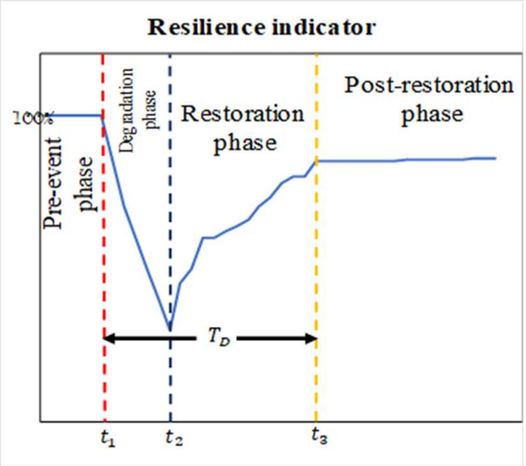

Figure 2: Graph of Resilience versus Time during natural disasters

Equation (10) implies the downtime reduces as resilience rises. Furthermore, there is a strong link with energy storage autonomy, T_{bank}, and uptime, T_U given by Equation (11) as:

$$T_U = g\left(T_{bank}\right) \tag{11}$$

A unique implementation of Equation (11) is further explored in the Case Study.

2.2. Energy Storage as an Important Resilience Component

The opportunity of including meaningful levels of storage that a microgrid offers cannot be under-estimated. This sub-section explains how energy storage can contribute to improving operational resilience based on loss of load frequency (LOLF) proposed in Panteli *et al.* (2017). The amount of necessary stored energy to ensure the stable operation is given by Toliyat and Kwasinski (2015) as in Equation (12).

$$E_{SS} \geq \frac{E_{\mu G}}{2\Delta f_{\max}} - \sum_{i}^{N}\frac{H_{gen,i}S_{gen,i}}{S_{base}} \tag{12}$$

where E_{SS} is the amount of necessary storage, Δf_{max} is the maximum allowed frequency deviation, H_{gen} is the microgrid inertia constant, S_{gen} is the rated power of each i generator, S_{base} is the microgrid power capacity, and N is the total number of generators in the microgrid. The impact of a 24-hour energy storage on the power system resilience has been proven in the Case Study.

2.3. Microgrid Controllable Resilience Analysis during Events

State controls have a quick reaction to the system's internal conditions because of their direct intervention. Within this section, the reliability of a power network is tested on the basis of LOLF, and the system's operating frequency and voltage through fluctuations are analyzed. The method was tested under extremely high wind speeds (40-60 m/s), which are reported to exist in hurricanes, which confirmed the feasibility of the suggested solution.

In general, the non-linear dynamics of the microgrid network can be defined as:

$$\dot{x} = f\left(x,t\right),\ x\left(t_o\right) = x_o \qquad x \in R^n \tag{13}$$

$$x = \begin{bmatrix} w & v & \Phi \end{bmatrix}^T \tag{14}$$

where w is the angular frequency, x is the state, v is the voltage, and ϕ is the angle of the flow. The Lyapunov variable in Equation (7) may then be written optionally as:

$$V = \frac{1}{2}aJw^2 + \frac{1}{2}bC\upsilon^2 + k\Phi^\gamma \tag{15}$$

where J is inertia, C is capacitance; a, b, k, and m are constants.

Let D be an area of γ size surrounding the origins:

$$D = \left\{X \in R^n : \left\|X\right\| \langle \in \right\} \tag{16}$$

V (0, t) = 0 and $V\left(x,t\right) \geq \alpha\left(\left\|Z\right\|^p\right) \qquad p \geq 2,\ \forall z \in D,\ \ \forall t \geq 0$.

That the definite is also positive, since

$$\alpha\left(\left\|Z\right\|^p\right) \to \infty \text{ as } Z \to \infty$$

$$V\left(x,t\right) \leq \beta\left(\left\|Z\right\|^p\right) \qquad p \geq 2,\ \forall x \in D$$

In the very same condition, $\forall t \geq 0$ renders this a decrescent feature. Therefore, the stability of the device can now be examined using the energy function in Equation (17).

$$\dot{V} = aJw\dot{w} + bC\upsilon\dot{\upsilon} + mk\Phi^q\ , \quad q = m-1 \tag{17}$$

$$i = C\dot{\upsilon} \tag{18}$$

$$\tau = J\dot{w} \tag{19}$$

As the microgrid provides electricity to the load, the current and torque may be considered to also be positive

$$\dot{V} = a\tau w + bi\upsilon + mk\Phi^q \tag{20}$$

By letting $a, b, k < 0$, q = 2, $\dot{V} < 0$, And the root according to the Barbashin-Krasovskii theory is globally asymptotically secure.

2.4. Case Study: 2008 Texas Hurricane Ike

As seen in Figure 3, a reduction in downtime and a rise in resilience after the inclusion of state control was accomplished. The initial based resilience values were taken from Table 1 and applied to the 2008 Hurricane Ike scenario in the Matagorda area of Texas. Throughout this case, these resilience parameters were estimated from real evidence and collected from the first time the tragedy was found until the moment the reconstruction process was finished. The typical up and outage times are also shown in Table 1. Time-dependent resilience variables were interpolated in between regression and the restorative phases at frequent intervals. Integration of the state control orders a significant storage level whereby results in an improvement in uptime as per Equation (11), this raises in uptime factors in a reduction in downtime, and a proportional rise in resilience values as per Equation (3). The corresponding response appears in Figure 3.

The effect of implementing the developed control is to minimize microgrid downtimes during the phases of deterioration and regeneration, which means a related rise in resilience between such phases. This reduces the size of the estimated V-shaped area.

The complete decline in downtimes could be represented by Equation (21) given as:

$$\xi = (t_{1S} - t_1) + (t_2 - t_{2S}) \tag{21}$$

Table 1: A List of Principles for Resilience, Uptime and Downtime (Kwasinski, 2016)

Parameters	Time
Resilience rate devoid of energy storage system	0.99
Resilience rate with energy storage system in one day of autonomy	1.00
Average uptime (in days)	25.78
Average downtime (in days)	0.16

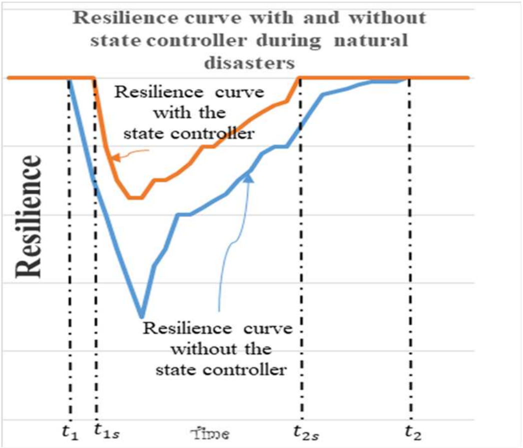

Figure 3: Resilience Curve with and without the State Controller during Extreme Events

3. RESULTS AND DISCUSSION

The previous analysis was validated with the use of a MATLAB/Simulink model shown in Figure 4. The distribution line was modelled with the following parameters:

$$\frac{R}{X} \approx 1 \text{ , Line length } = 0.5 \text{ km}$$

These are consistent with the fact that in microgrids there is not necessarily a predominant inductive impedance component observed in conventional large power grids.

The source is connected through a 1 kV bus to a resistive 1 kV distribution system. A three-phase two winding 1/0.208 kV step-down transformer was used to step the voltage down to 208 V line-line when servicing a local load. Figures 5 through 9 show the simulation results. Figure 5 depicts the system's frequency changes while it was just weakly loaded. Figure 6 shows the frequency fluctuations when the load was raised to 2 MW. The stability of the system was found to be significantly impacted as the system's load rose.

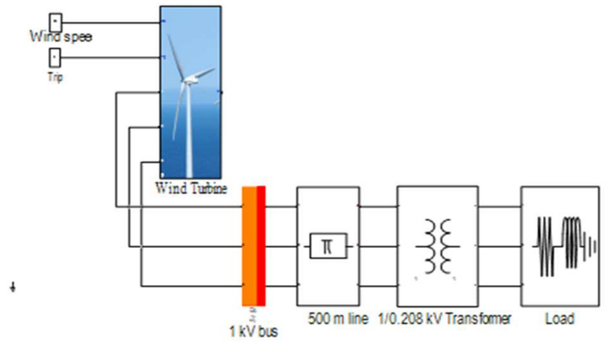

Figure 4: Schematic of the Test System Extreme Events

In Figure 7, the minimum value in the transient indicates a frequency of 59.98 Hz. This value is indicative of a potentially unstable equilibrium point, in which a consistent fluctuation in frequency beyond an acceptable limit of ±0.5 Hz could lead to system shutdown. In order to avoid this condition, the resilience parameter indicates an anomaly that is transmitted to the state controller, which, in turn, commands the energy storage device to support the microgrid within its autonomy capacity. The results obtained above are improved with the presence of a controller, which efficiently manages the MEMS during system disturbances.

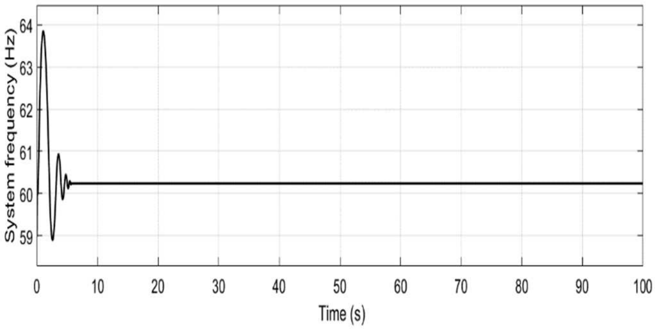

Figure 5: Frequency of the System during a 10 kW Light Load

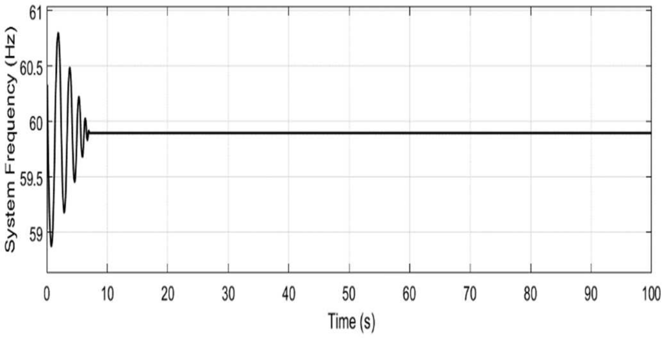

Figure 6: Frequency of the System when the Load is Increased to 2 MW

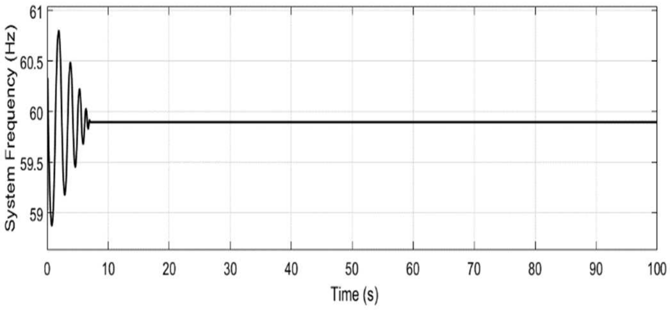

Figure 7: Frequency of the System when H = 5 S

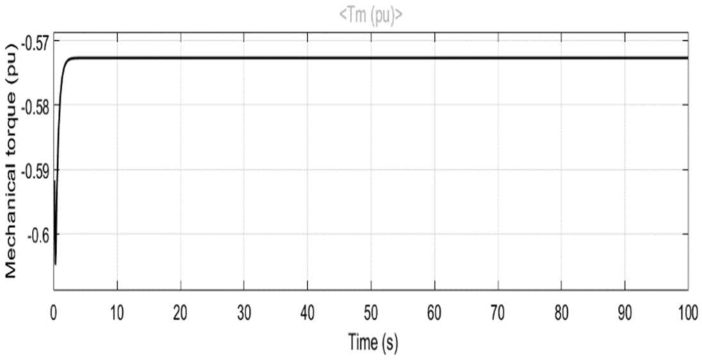

Figure 8: Mechanical Torque of the System when H = 5 S

Figure 9 indicates the frequency obtained when the state controller had been added to the system. The system frequency was maintained at 60 Hz in Figure 9, which is maintained to allow for the efficient operation of the microgrid during and after extreme events, and it indicates a more resilient system as compared to the frequency data obtained in Figure 7. The obtained direct-axis, V_d and quadrature-axis, V_q voltages are 1.021 p.u. and 0.07148 p.u. respectively. Hence, the stator voltage V_S is given as:

$$V_S = \sqrt{V_d^2 + V_q^2} \tag{22}$$

$$V_S = 1.023 \text{ p.u.}$$

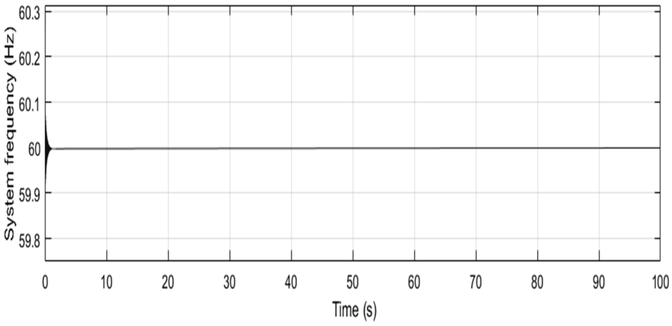

Figure 9: Frequency of the System with a State Control

The stator voltage is the grid voltage and hence an indication of a more resilient system during natural disasters. This is within the limit of the operating voltage setpoint. At this operating condition, the microgrid can thus maintain its functions to an extent during extreme events whereby preventing total system collapse.

4. CONCLUSION

The findings were able to show a state control's commitment to enhancing resilience while allowing unified control and effective operation of the microgrid energy network under adverse environmental conditions. Under these conditions power generated is affected. Furthermore, the changes in load may be sudden. Each of these factors influences the voltage and frequency stability of a microgrid network and may result in a failure if it is over a certain operational limit. Any portion of the load does not obtain power during such shutdowns, portraying excessive downtimes. A scheme for controlling the microgrid was proposed utilizing a state estimate of microgrid system limits to soften this effect. The state control was activated after an analysis of Hurricane Ike to improve program resilience. This work confirms an improvement in the resilience of the microgrid during extreme weather effects using a state controller. The proposed state control uses the state parameters to synchronize the operations of the system. A major contribution of this research exists in the microgrid regulation centered on quantitative resilience indicators.

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