Electricity Distribution System Resilient Control System Metrics

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***Abstract*—In order to assess the resilience of a system, a set of measures must be defined. Varying control architecture while considering such a system of metrics targeted at resilience can determine the relative merit of the architectures with respect to the resilience of the system. Traditionally, electricity distribution is concerned with delivery of power from transmission or sub transmission to consumer loads with basic control of tap changing transformers and capacitor banks to regulate delivered voltage and provide reactive power support, respectively. In the near future, modern distribution systems architecture are anticipated to include substantially more controllable assets enabling more complicated control architectures to optimized based on reliability and economics. This paper reports on the definition of resilience metrics developed for modern distribution systems for delivery of electricity. Specifically, the metrics are focused on adaptive capacity related to the scale for which the system is able to resist, respond, recover and restore after disturbances in real or reactive power and time requirements to respond and restore the system to a complete normalcy.**

I. INTRODUCTION

Current considerations of power system reliability have led to the development of several metrics that primarily reflect loss of service, which are used in some sense as a basis to justify future modifications. However these metrics, while beneficial, are not intended to holistically and directly consider the power, control and communications (cyber-physical) dynamics that establish designs with inherent resilience to natural and man made disturbances. As the current power system evolves, introducing a greater amount of destabilizing influences from uncontrollable generation, an understanding of how resilient the resulting design is to disturbances will be a necessity [1]. Claimed improvement of resilience, such as distributing control loops to intelligent agents at lowest levels with ability to recognize precursors to faults [2], require a measurement. Time scale of disturbance in combination with the percent of effected customers in distribution systems considering the effect on critical loads to a small set of specified disruptions was proposed as a resilience metric in [3]. Our paper takes a more general approach define resilience to understand the ability of the distribution system to adapt dependent on the assets available. Previous work, focused on individual stability of active control system components for an understanding of an asset's adaptive capacity [4] is extended to the measurement of distributed assets by using a "manifold" to measure adaptive capacity across multiple dimensions including time. The metrics consider temporal flexibility of active and reactive power to measure the maximum size disturbance amplitude and duration due to cyber and physical disturbances that can be withstood. This approach is applied to a modern distribution system (MDS), which considers large integration of distributed energy resources (DER).

The paper first provides the problem statement in Section II, which overviews a metrics basis for resilience and define a framework for a MDS. In Section III the metrics basis is extended to the physical and temporal dynamics of a power system, both real and reactive power assets, for aggregations of controllable generation and loads. In Section IV, the framework for aggregating metrics across the architecture of the MDS is developed. The resulting manifold is mapped to a base metric of disturbance size and duration to maintain minimum normal operation. Finally, conclusions and ongoing work are reported in Section V

II. PROBLEM STATEMENTS

Stability of the power grid is defined in terms of voltage and frequency across the grid. Frequency stability requires balancing the real power (P) generation and load, combined with losses to maintain frequency of what is a distributed electromechanical system buoyed by rotational inertia of the prime movers that turn the generators. Voltage stability requires the balancing of reactive power (Q) across the network. Thus metrics must address P, Q and be extensible across the grid network. Distribution has traditionally been concerned with maintaining the connections between the distribution substation and the loads, where reliability might be enhanced from a radial network to one that contains redundancy in some paths by providing meshes with ability to switch around branches that are out of service. MDS resilience metrics must consider the future, which is predicted to include high penetration of DER in generation, controllable loads, storage, and other flexible assets. Control of these devices have many purposes, which include support of regulation of voltage and frequency across the distribution network, economic benefits to the owner by selling services to the grid, and reliable utilization of interconnections, e.g., power lines, transformers, switches.

The desired outcome is a mapping of the capabilities and limitations of a distribution system to the resilient control metrics that express the “Rs” of resilience, i.e., Recon, Resist, Respond, Recover, and Restore, notionally in the “Disturbance and Impact Resilience Evaluation Curve” (DIRE). Fig.1 shows the notional DIRE curve, which expresses the relative performance of the system relative to optimal and the minimum performance level or Resilient Threshold that the system is expected to maintain to be considered resilient. The temporal demarcations include: t_i-the time the disturbance initiates, t_{Bi}-the time the performance falls below minimum normalcy if system becomes brittle, t_R-time of the resolution or minimum level of performance occurs, t_{Bf}-time of achieving minimum normalcy, t_{f1}-time of transition from system response to the restoration response.

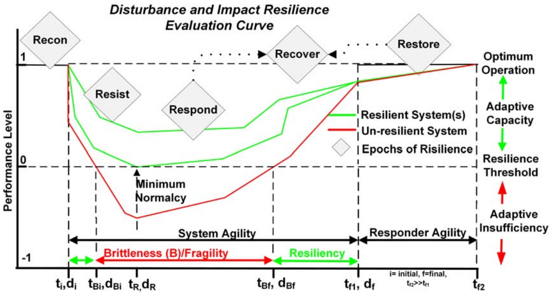

Fig. 1: The DIRE curve showing the time delineations of the 5R’s of resilience

As might be expected, the magnitude and duration of a disturbance that can be withstood is dependent on the ability of a system to Resist and Respond. Resist describes intrinsic or immediate responding properties of the system; where, Respond relates short latency and close proximity assets that engage automatically. To Restore, and to fully Recover, requires longer latency actions, where remote proximity of assets must engaged at the end or near the end of the disturbance to bring system up to optimal operation minus depleted resources. Restoring may involve repair or maintenance of degraded assets and recharge of depleted resources. A logarithmic time scale on the DIRE curve is appropriate under most applications as Resist is on the order of seconds and Restore may be months or longer. Metrics for MDS need to be mapped to the notional DIRE curve.

III. DISTRIBUTION SYSTEM ASSET METRICS

The extensibility of the metrics in a manner that is extensible to uncertainty of availability due to communication, security, or natural effects is necessary to measuring the resilience of the MDS. This section describes the method for accounting for capabilities, such that, those affects can be analyzed in future steps in the metric development.

A. Asset Description

Assets in a distribution system need to be described in terms of power, energy, latency, and rate of change limits. When these limits can be describe in a simple, yet sufficient, form, the assets can be aggregated in a manner that is tractable. This description must convey the "margin to maneuver" (M2M) that an asset has to respond to a disturbance. This description can describe an entire asset or the amount of an asset's capability that is set aside to respond to unanticipated changes. An example of an asset that is partially available is a generator that has been dispatched to produce 0.8 of maximum power output leaving 0.2 of that level available in a flexible manner.

1) Apparent Power Limits: M2M is found to be in sum of the range of control available among the generators and loads. M2M is considered for both reactive and real power. The range of a component is represented by a region of the apparent power plane over which it can be applied. From an analysis and design perspective the range and any discrete steps of the choice in control must be considered. For example: a distribution static synchronous compensator (DSTATCOM) may be adjusted continuously whereas a capacitor bank is either on/off or has discrete steps as individual sets are switched in and out. An asset, k, is described in terms of real power ($P_k\text{max}$), reactive power ($Q_k\text{max}$), and overall apparent power limit ($S_k\text{max}$). For purpose of this paper, a generalization is made that the interdependent limits of a device that can provide a combination of P and Q is limited on S by the following constraints at a time t of

$$P_k(t) \leq P_k\text{max} \tag{1}$$

$$Q_k(t) \leq Q_k\text{max} \tag{2}$$

$$\left(P_k(t)^2 + Q_k(t)^2\right)^{1/2} \leq S_k\text{max}. \tag{3}$$

Some examples of controllable assets are shown in the complex apparent power plane of Fig. 2.

2) Energy Limits: Some assets are energy limited. The battery is the simplest example to describe. A half full battery can move either direction to supplying or absorbing power but is limited by the storage capacity on one end and depleted battery on the other. Buildings are another example that have the ability to have a temperature set point one direction or the other to accomplish a similar result in reducing load or increasing load. The building tenants likewise will not be adversely effected by small changes; however, once the building hits steady state, there is no more power compensation available without unwanted discomfort to personnel and/or equipment. Both show example of resources that could be controlled up to a maximum power level but only for a finite amount of time. Until the asset is recharged in a restore phase, the resource cannot be used again. The power adaptive capacity must go to zero once the energy available and the beginning of use has been expended.

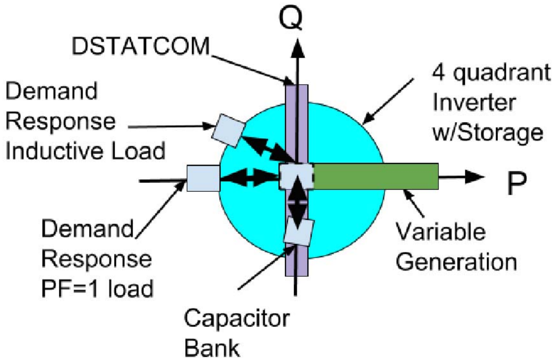

Fig. 2: Complex power plane with examples of the range of control of controllable assets

B. Energy and Power Asset Parameters and Bias Considerations

The assets are described through parameters such as for asset c_k the parameters:

- $P_{c_k m}$ and $P_{c_k M}$ - limits of real power level of device m for minimum and M for maximum,
- $Q_{c_k m}$ and $Q_{c_k M}$ – limits of reactive power, and
- $E_{c_k m}$ and $E_{c_k M}$ - energy limits in the device.

. Some devices have all four quadrants of power and are apparent power limited, such that $S^2_{c_k M} > P^2_{c_k} + Q^2_{c_k}$. Minimum limits on power and energy maybe be negative and the adaptive capacity will depend on where the asset is currently biased. For this paper, assets are assumed to be neutrally biased to allow a command either direction, that is $P_{c_k}(t) = (P_{c_kM} - P_{c_km})/2$, $Q_{c_k}(t) = (Q_{c_kM} - Q_{c_km})/2$, and $E_{c_k}(t) = (E_{c_kM} - E_{c_km})/2$. The control system may be designed to drive the bias in a direction that is optimized for the situation. For example with a battery storage system, the neutral bias for energy would be half full but anticipating a later need to absorb real power may influence the designed bias. A system that accurately anticipates would improve on this metric by controlling the bias. Of course, consequence exist if a disturbance, true to form, is in the opposing direction.

Temporal constraints of the assets' capabilities can be describe in two terms: latency to actuating and agility. The agility is the maximum rate of change of an asset and the latency is a delay in availability of the asset. An energy constraint manifests in inability to apply real power due to the energy resource becoming depleted or reaching maximum capacity. The energy limit is another constraint restricting the duration for which the asset can be applied. The full description of the S-plane manifold specifies the maximum adaptive capacity over time. The complex shape is bounded by the rollup of the adaptive capacity with rate constrained by the agility of the components and any pure latency. The surface extent changes based on agility up to the maximum magnitude available and continues in that direction until energy is depleted and the P goes to zero. Additional parameters need to be added to the description for time:

- α_{c_k} - time constant related to the maximum rate of change in $P_{c_k}(t)$
- λ_{c_k} - pure latency to engaging $P_{c_k}(t)$
- β_{c_k} - time constant related to the maximum rate of change in $Q_{c_k}(t)$
- μ_{c_k} - pure delay latency to engaging $Q_{c_k}(t)$

C. Intrinsic assets

Examples of intrinsic assets include, the available flow through the connecting power lines of the distribution system and rotating inertia of synchronous machines. These assets are interconnected in the case where significant rotating inertia is available compared to the "strength" of the interconnecting power line. This will become an important aspect in considering microgrids or grids of microgrids that are have small prime movers as assets or can provide a certain amount of synthetic inertia through control of storage resources.

1) Spinning inertia: Although typical distribution systems do not have significant inertia, even a small amount of inertia, added by DER, could be important to short term support and consideration of whether the systems other slower or longer latency devices can be activated in time. Considering a portion of a distribution network as a lumped component the first dynamical equation relating to temporal resilience is the mechanical inertia kinetic energy as captured in the swing equation [5]:

$$J_i\omega(t)\frac{\partial\omega(t)}{\partial t} = \Delta P_i(t) \tag{4}$$

where J_i is the sum of the moment of inertia in the segment of the grid under consideration, ω is the rotational velocity of the spinning moments and ΔP_i is the imbalance in generation and load power in the segment i. For a set of machines on the segment of the distribution system this can be written in terms of alternating current frequency, $f(hz)$, as

$$K_i(f) = (2\pi f)^2 \sum^{l} \frac{J_l}{N_{p_l}^2}, \tag{5}$$

where N_{p_l} is the number of magnetic poles of the synchronous load or generation for the lth asset.

If the nominal frequency is f_o and the range of operation is $f_o \mp f_r$, the minimum and maximum kinetic energy levels from f_o is

$$K_{i_m} = (2\pi(f_o - f_r))^2 \sum^{l} \frac{J_l}{N_{p_l}^2} \tag{6}$$

$$K_{i_M} = (2\pi(f_o + f_r))^2 \sum^{l} \frac{J_l}{N_{p_l}^2} \tag{7}$$

Given frequency before a step power disturbance, P_d is nominal the kinetic energy available to absorb the disturbance is the difference in the nominal energy and the limiting range given the direction of the disturbance, thus

$$K_{i_a} = \begin{cases} K_i(f_o) - K_{i_m} & \text{for } P_d < 0 \\ K_{i_M} - K_i(f_o) & \text{for } P_d > 0 \end{cases}. \tag{8}$$

The time limit for response from other assets, t_r, is then available amount of energy divided by the magnitude of the disturbance in units of power,

$$t_r = K_{i_a}/|P_d|. \quad (9)$$

2) Grid Connection: Initially assuming no limits on voltage at the end of the connecting power line, the power support from the connected network is limited to the physical transport elements, e.g., transformers and distribution/transmission lines. The apparent power limit for the line, d, connecting the segment of distribution is

$$S_d\text{max} \leq V_d V_s / X_d, \quad (10)$$

where X_d is the reactance of d, V_s is the voltage at the far end of the connecting line (assumed "stiff") and V_d is the voltage at the near end. Alternatively, the limit on the connection may be thermal limits due to maximum conductor temperature and be set by

$$S_d\text{max} = I^2_{\text{max}} R_d. \quad (11)$$

The limit on S defines extents of P and Q through:

$$S_d\text{max} \leq (P_d(t)^2 + Q_d(t)^2)^{1/2}. \quad (12)$$

Here, the limit is physical “pipe” limit not the voltage stability limit.

D. Concise asset description

The asset can be described by showing the limits as a function of time from the disturbance. The bounds as time varies provides the extent an asset can be utilized in the S-plane with energy limits applied. Fig. 3 shows the time varying abilities of a storage asset with reactive power capabilities. With polar coordinates the extents in the S-plane are described as a time varying shape, $S(\theta, t)$, where θ is the angle, power factor, with which the device is commanded and t is the time from the disturbance and the application of the device. Since Q is not energy limited, once any P has exhausted the energy reserve, the full capabilities of Q of the device are available. A specific example of this type of asset is a power inverter that has storage and reactive element to support both P and Q in all four quadrants of the S-plane.

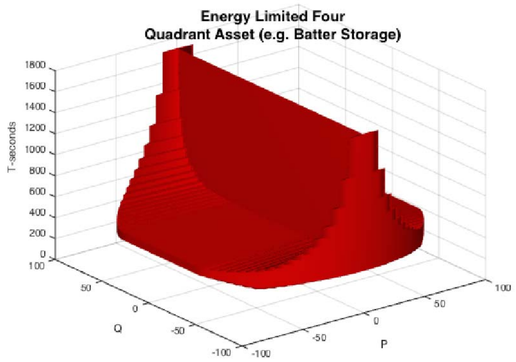

Fig. 3: A visualization of abilities of an energy limited asset possessing both P and Q

IV. MDS METRICS

The assets next need to be considered as groups logically according to the topology of the connecting network.

A. Economic Unit

A cartoon is used to define the economic unit (EcU) considers an aggregation of uncontrollable and controllable elements.

1) Steady state Adaptive Capacity: From a steady state perspective each component attached to drops of a distribution network has an apparent power range over the complex S plane, $S = P + jQ$. The relevant control goal for a distribution network is to drive $S = \sum_i Si = 0$. Each component of the distribution network can be segmented into controllable, P_c and Q_c and non-controlled parts, P_n and Q_n, portion of the apparent power, S :

$$S = (Pc + Pn) + j(Qc + Qn). \quad (13)$$

Fig. 4 portrays the concept of controllable versus uncontrollable aspects of aggregation. The cloud portion of the figure illustrates the variable aspects and the solid element represents the available extents of the controllable portion without considering time in the response. This notional representation also shows the difference between a system that has adaptive capacity versus an adaptive insufficiency and provides a possible allocation for operational normalcy, with the delineation of a critical load.

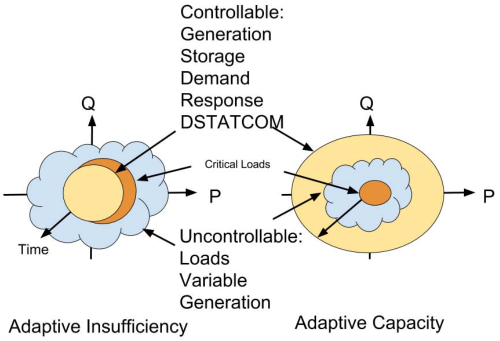

Fig. 4: Cartoon that illustrates the capabilities of controllable assets versus uncontrollable elements and critical loads

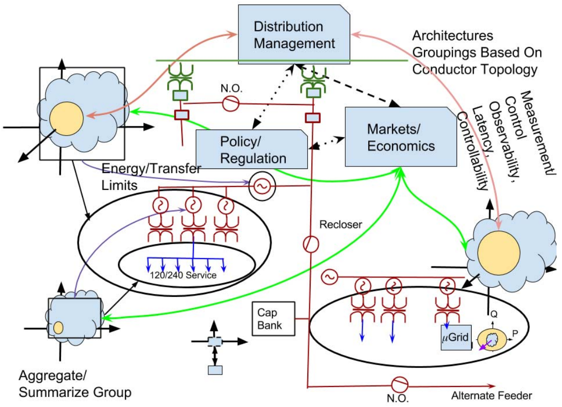

Fig. 5: Rollup of M2M in a partial primary mesh distribution system

Fig. 5 illustrates some logical sets of MDS assets and the aggregation of those assets including a representation of the limits, control interaction, and markets. Some elements and branches will possess greater degree of flexibility. The EcU is an aggregation of a portion of the MDS that for the purpose of this paper relates to the physical topology. The EcU is supported by the upstream grid connection. Controllable aspects of the grid may be grouped by ownership or markets; however, that is left for future work that include details of economics.

2) Adaptive Capacity Aggregation for an EcU: A raw adaptive capacity of a grouping of assets reflects the flexibility that is present in that grouping as an economic unit or an aggregation of a cut section of the distribution system. Adaptive capacity of a group of elements should also be considered in the context of the topological position in the distribution network. We assume the use may have on upstream distribution, i.e., dynamics in this aggregation is not large enough to change the boundary condition voltage, the transmission asset is additive to the controllable asset power domain. The measurement and compensation for any voltage disturbance is an operational consideration, which is neglected for as metrics are used in design. Considering the limits in the S plane, the limits on any continuously variable asset is represented as a closed contour similar to the cartoons mapped onto the S plane previously shown, in Fig. 4. The limits of the assets can be summed by expressing in polar coordinates, and adding the magnitude for common elements by describing the limit as $S_{c_k}(\theta, t)$ and summing the relevant assets the total adaptive capacity in the real and reactive power is

$$S_{\text{AC}}(\theta,t) = \sum_{k=1}^{N} S_{c_k M}(\theta,t), \tag{14}$$

over N assets in the domain one of which is the upstream interconnect limit, $S_{c_{\text{up}} M}(\theta,t)$. Assets with discrete control, e.g., capacitor banks, are treated as a special case in the aggregation along the Q axis.

B. Resilient Metrics in Context of the Grid Topology

The topology is now considered with respect to adaptive capacity and agility of the EcU and the ability for that capability to be exported outside the EcU.

1) Adaptive Capacity: Analysis can now be made of the sufficiency of the adaptive capacity by considering the range of historical or expected non-controllable assets in the aggregation. The shape of the cloud is the maximum magnitude of that history mapped out radially in the S-plane, S_n, forming the tangible form of the “cloud” in the cartoon. The net adaptive capacity described in the asset aggregation manifold in eq. (14) is

$$S_{\text{ACnet}}(\theta,t) = S_{\text{AC}}(\theta,t) - S_{\max_n}(\theta), \tag{15}$$

where

$$S_{\text{max}_u}(\theta) = \max_t S_n(\theta, t), \tag{16}$$

defining the historical or anticipated maximum of the elements that are non-controllable. The minimum across all angles, if it is greater than zero then defines the margin of this portion of the system that is available before hard curtailment of load or generation would be the recourse for mitigating the disturbance.

By excluding the upstream component from the total adaptive capacity, the exportable adaptive capacity of those assets is:

$$S_{\text{ACex}}(\theta, t) = S_{\text{AC}}(\theta, t) - S_{c\text{up}M}(\theta, t). \tag{17}$$

This neglects the loss of the export that is dependent on the resistance of the line, R_u. The aggregation at the boundary can then be added together with other branches that attach at that bus, in a similar manner as eq. (14) at the next level of aggregation.

Considering the adaptive capacity in the energy, a one dimensional domain that sums up the minimum and maximum energy storage including the kinetic energy of any rotating inertia. Another way to look at this is the same as the S-plane but restricted to one only the real axis since energy is the integration of real power:

$$\left[E_{\text{TOT}M}, E_{\text{TOT}m}\right] = \left[\sum_k E_{c_k M}, \sum_k E_{c_k m}\right]. \tag{18}$$

The rate at which the energy can be utilized is dependent on the power limits of the asset for the controllable assets with real power capability. While the kinetic energy of the inertia is not controllable, per se, the rate at which the adaptive capacity is consumed depends on the moment of inertia and the magnitude of the disturbance.

2) Agility: Agility is determined in a similar manner by the time constants in the controllable assets at the time the derivatives of generation and load diverge. The difference between derivatives provide the instantaneous agility where the extreme values of the derivatives in historical or worst case scenarios establish the limiting levels of agility at the critical points. The mathematical expressions for agility relates to the combined rates at which assets can be applied. Summarizing the set of controllable assets are described by the sum of the maximum rate of change:

$$\text{Ag}_S = max_{(P,Q)} \left(\sum \frac{dS_{c_k}(t)}{dt} \right), \tag{19}$$

shown as dependent on the P and Q which we will simplify to consider the case that we are not at the limits of either P, Q, or total S. At those points the a change in a give direction may be constrained to zero, e.g., $P = P_{\text{max}}$ where Q is fixed to zero and $dP/dt < 0$. This notation is used to evaluate the maximum rate of change that can be commanded. We assume a symmetrical rate of change but the method can be extended to adapt to a more complex notation if power factor is a dependency in any assets.

Agility for the energy facet of adaptive capacity is not addressed independently as the rate of use of energy is directly found through the integration of the real power applied by an asset that is energy limited. The concept of where the control system drives the bias will relate to how quickly energy assets will be depleted, thus removing the ability to supply or absorb real power by that asset.

C. Example aggregation

Fig. 6 shows an example of some arbitrary assets that are combined. The graphic describes the flexibility of the asset or system of assets assuming the assets are applied at the maximum rate at specified power factor angle up to the maximum apparent power level of the specific real or reactive limit is reached. A Matlab script was written to generate the shape for all θ, i.e., power factor that can be applied to a disturbance for assets that are neutrally biased with respect to maximum adaptive capacity of real or reactive power. This description also assumes a neutrally bias on the energy stores so there is equal availability in the negative and positive direction.

D. Mapping to DIRE Curve

As promised, a direct mapping to the DIRE curve is now developed from the combined asset example shown if Fig. 6. The end result is determination

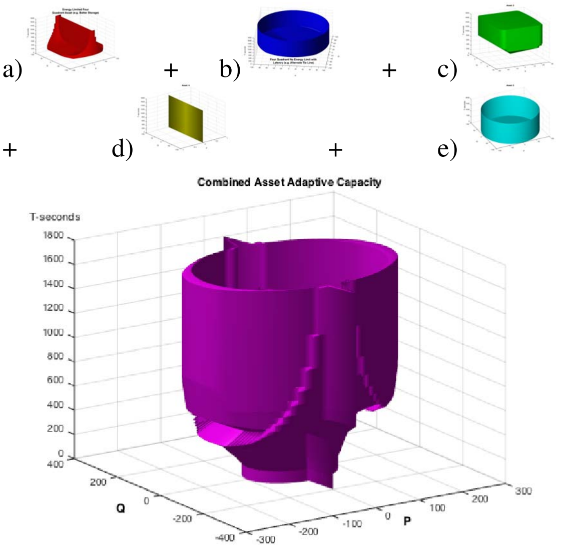

Fig. 6: Example combination of assets shown individually and in sum. Assets: a) energy limited four quadrant, e.g., battery, b) non-energy limited with high latency, e.g., alternate tie line, c) asymmetric P/Q-conjectured, d) DSTATCOM, and e) low latency four quadrant with no energy limit

of the magnitude and duration step function disturbance in an arbitrary direction in power factor. The limiting case being the nearest direction of aggregation to the intrinsics limits, resistance phase. The maximum sustainable duration for the disturbance is determined by energy limits available to continue to support the limiting magnitude, response phase. Once the disturbance is resolved, the amount of energy available to replenish energy reserves to levels prior to the disturbance can be assessed by determining the amount of time needed to do so in the recover phase. Finally, the restore phase will pertain to any degradation caused in the disturbance or response to assets or infrastructure that requires maintenance, repair or replacement. The following example maps the set of assets onto the extreme of the historical or predicted worst case with respect to the limits of upstream support.

1) Resistance: Resistance is a rate of change metric, where intrinsic properties such as inertia, fast responding assets and acceptance tolerance to nominal voltage and frequency are considered. These determine the slope of the DIRE curve and relate to how much time do slower responding assets have to react. Avoiding a frequency stability “trips” to machines, requires the instantaneous support from connected spinning inertia be great enough to remain above frequency limits until short latency devices engage.

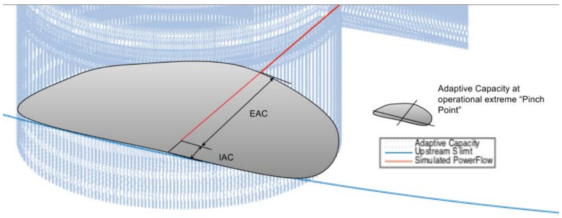

Fig. 7: Zoomed details of the clipped asset

In this example the range of the assets exceed the limit of the intrinsic capability of the power line connecting to this EcU. Shown in detail in Fig. 7, the ability to utilize the full extent of the adaptive capacity is clipped by the intrinsic limit of the connecting power line. The clipping is not a serious problem since the limiting disturbance that would utilize this capacity would be the diameter of the intrinsic limit, i.e., much larger than the maximum sustainable disturbance in an arbitrary direction. The illustration in Fig.7 is a graphical representation of the analytical expression in eq. (17).

2) Response: The sustainable duration of the disturbance relates directly to the time period that the shape of the capabilities curve or manifold remains outside the cylinder of the resistance level. This allows for slower responding assets to be engaged before intrinsic and immediate responding assets become depleted. The point where that occurs would cause a failure to occur in the connecting power line. The response support time frame is finite with it is limited by energy constrained assets.

3) Recover and Restore: Recovery is the longer term evaluation of the systems ability to restore bias points in the adaptive capacity in the S-plane and the energy field. A integration of the time consideration of adaptive capacity of the disturbance impacts from $t = 0$ out to the engagement of shortest latency assets in the control space combined with voltage and frequency tolerance and credit for rotational inertia, provides a measure of resistance. What is the resulting voltage and local frequency response (given any inertia) at time frames of less than a minute can be analyzed through the application of the time varying adaptive capacity. This work has not been completed in full form to date.

Recovery is an analysis of the time to recharge the system per the size of the disturbance. Once the system has relaxed from the disturbance and reaches times of available capacity that can be used to bring energy biases back to center. The Restore phase though not directly addressed in this paper anticipates degradation or damage that requires additional time and investment to completely return the system to optimal operation.

The mapping to the DIRE curve is illustrated in Fig. 8. Resist mapping to the intrinsic support of the assets that act as a physical process or very fast and low level control loops designed to react without supervisory decision, like synthetic inertia. Restore period consists of the capacity of short to medium time period use. Finally, recover are the portion that is required to bring the assets that have been depleted back to bias points where they would again be available to respond to another disturbance. Total P, Q, and E that can be applied over a given time period defines the magnitude and duration of disturbance that can occur without dropping below minimum normalcy as defined by the stakeholders.

V. CONCLUSION AND FUTURE WORK

This paper presents a development of resilient control metrics as applied to the operation of a modern distribution system that implies more flexible assets and potentially complex distribution control methodology. An easily aggregated accounting of the properties of assets available including maximum applied power values, maximum rate of change of the application of power, energy limits, and latencies has been developed. An example of the determination of the magnitude and duration of a disturbance was shown. In the present form, this work provides a design tool to decisions about the value of a applying a group of assets to a distribution system which is poised to measure the relative merit of possible control schemes that in themselves shape the abilities of the assets through additional latencies or introduction of time constants with control laws. The description of assets provides a means for subsystems, economic units, to convey capabilities to the larger system.

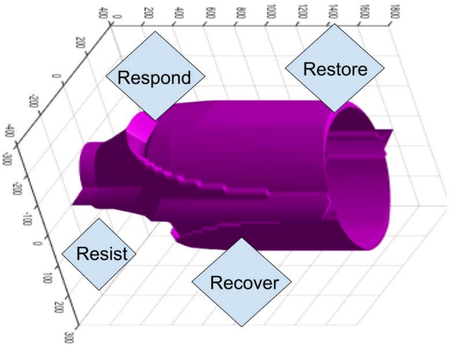

Fig. 8: A mapping of agility and adaptive capacity to the temporal ranges of Resist, Respond, Restore and Recover

This paper sets a basis for describing the influence of cybersecurity and human in the loop through the application of effects in those domains in future work. For example in the cybersecurity, the potential effects of multiple types of impacts can be addressed:

- Denial of service – increased latency
- Disruption of communication channel – asset becomes uncontrollable
- Control System Compromise – asset control law set to do opposite of command.

Further, we anticipate a potential use of the description as a tool to provide operation metrics capable of supporting situational awareness of operators and stakeholders, including a mechanism to communicate capabilities of Economic units to markets and regulators.

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