Methods for Analysis and Quantification of Power System Resilience

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Abstract—**This paper summarizes the report prepared by an IEEE PES Task Force. Resilience is a fairly new technical concept for power systems, and it is important to precisely delineate this concept for actual applications. As a critical infrastructure, power systems have to be prepared to survive rare but extreme incidents (natural catastrophes, extreme weather events, physical/cyber-attacks, equipment failure cascades, etc.) to guarantee power supply to the electricity-dependent economy and society. Thus, resilience needs to be integrated into planning and operational assessment to design and operate adequately resilient power systems. Quantification of resilience as a key performance indicator is important, together with costs and reliability. Quantification can analyze existing power systems and identify resilience improvements in future power systems. Given that a 100% resilient system is not economic (or even technically achievable), the degree of resilience should be transparent and comprehensible. Several gaps are identified to indicate further needs for research and development.**

Index Terms—**Power system resilience, reliability, emergency response, restoration, recovery, planning, operation, operator training.**

I. Resilience as a Distinct Concept

RESILIENCE is an emerging technical concept in power systems and other infrastructures. As a relative latecomer to the technical analysis of engineered systems, it needs to be carefully demarcated with respect to the existing notions, particularly reliability, robustness, and security. This task is not straightforward, as these other concepts are evolving as well, driven by technological advances. Some distinctive properties of resilience include:

- A somewhat simplified view of reliability and resilience as practiced today is the type of events they offer protection against: reliability refers to high-probability, low-impact (HPLI) events (for which power systems have been traditionally designed and operated), while resilience refers primarily to high-impact, low-probability (HILP) events. It is of course possible to include/exclude some aspects of HILP events in the reliability calculations via "Major Event Days" as defined in IEEE Std. 1366 [1] and other classes of exceptional events.
- Robustness is a system's intrinsic, scenario-independent property to remain stable and perform satisfactorily in the presence of uncertainties in the system and its environment; robustness is often embedded in the component design and operation. Restoration and recovery portions of resilience

Manuscript received 27 April 2022; revised 28 September 2022; accepted 3 October 2022. Date of publication 10 October 2022; date of current version 21 August 2023. The work of Rodrigo Moreno was supported by ANID, Chile, under Grants PIA/APOYO AFB180003 (Instituto Sistemas Complejos de Ingenieria (ISCI), and Fondecyt /1181928. The work of Aleksandar M. Stankovíc was supported in part by NSF under Grant ECCS-1710944, in part by CURENT Engineering Research Center of the National Science Foundation and the Department of Energy under NSF Award EEC-1041877, and in part by ONR under Grant N00014-16-1-3028. Paper no. TPWRS-00576-2022. *(Corresponding author: Aleksandar M. Stanković.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPWRS.2022.3212688.

Digital Object Identifier 10.1109/TPWRS.2022.3212688

add an active, scenario-dependent component, embedded in system operating procedures and human decisions (starting with the response portion during the resilience event).

- Resilience analyses often reveal strong couplings with other infrastructural systems (communications, water, transportation, natural gas), and in some cases necessitate a joint analysis.
- Today, reliability is paid for by the customer, while resilience payments may include society/tax-payer because of its social impact (following a disaster area declaration by state or federal governments). There is, of course, a significant commonality here, as these societal groups largely overlap, so a new class of cost-benefit and risk analyses is needed to properly quantify resilience.
- Resilience-driven investment decisions can be significantly different from the N-1-based security (and its variants such as N-2) and reliability-driven investment decisions.
- Community impact and community response are key aspects of resilience. It is thus challenging to fully describe resilience events from their impact on the electric power system alone.

Our analyses point toward the need to perform reliability and resilience studies as separate but coordinated activities.

Decision paths and processes activated during resilience events are normally not exercised in day-to-day operation, thus justifying a separate study of resilience and specific requirements for operator training.

Many countries throughout the world face an ongoing challenge of protecting their critical infrastructure from significant equipment damage caused by extreme natural events such as weather or geomagnetic storms, man-made events such as physical and cyber-attacks, or errors in operation.

As many of these natural hazards and threats from outside actors continue to increase in both frequency and intensity, the efforts of owners and operators to enhance the resilience of their systems and assets are more crucial than ever. Furthermore, the trend toward electric transportation and heating/cooling increases these sectors' dependence on the electric power system and the growing penetration of information and communication technology (ICT) creates new dependencies.

Low and average impact, high-frequency events that are analyzed by reliability engineering generally tend to be numerous and to affect a smaller number of people for relatively short time intervals - minutes to hours.

Resilience in contrast deals with extreme events that happen rarely in a longer horizon (years or decades) and affect many people and/or have a long duration. Largely because of global climate change, extreme weather events such as hurricanes, ice storms, floods, and droughts have become more frequent in recent decades and their strength and duration are also intensifying [2], [3]. As a result, electric power systems may suffer more severe impacts, particularly with renewable sources being more exposed to the weather.

II. Regulatory Frameworks

Appreciating the fact that grids across the world are diverse as is their governance, the resilience of any critical infrastructure can only be provided by engaged and coordinated governance at all levels, which can typically be classified as international, federal (or national), state (or regional), and local.

Ideally, all infrastructure planning policies and decisions should be consistent and complementary at all levels, thus avoiding unintentional and potentially detrimental effects of discrepancies. One way to achieve this is by iterative cycling through regulatory (top-down) and community (bottom-up) resilience alignment. Realizing that every geographical area is unique with regard to resilience events and critical infrastructure, resilience may be somewhat of a developing concept to some policymakers. It could solicit differing definitions and levels of importance in the policies, thus complicating infrastructure resilience coordination.

When there are different policymakers for each societal infrastructure element which are often overseen by different governmental and regulatory bodies, coordinated forward action to implement resilience policies may be difficult. The results of this process are industry or even utility level resilience policies (bottom-up). Key in building consensus, and laying a foundation for action, will be utilizing available data from all sectors and all types of customers. Regulators at all levels should adopt policies requiring sectors to develop coordinated resilience structures (top-down).

Existing emergency management systems serve as a superb basis and coordination frameworks should be used as a template. Most progress toward improved power system resilience policy must be approved by government regulators and policymakers with input from all stakeholder representatives, and thus require quantification of resilience societal and economic benefits to justify the expense. This cost-benefit analysis process should provide the answers to many starting point questions as what is the present level of reliability and resilience, what level of resilience is wanted/needed, how can that be best achieved, who will pay for it, etc.

III. Conceptual Definitions

Discussions of resilience as a feature of complex systems are numerous – a 2018 review [4] and the follow-up dialogue mention over 10,000 relevant references. Many of the modern notions of resilience have been influenced by the works in ecology, with some seminal contributions by Holling: "*the capacity of a system to absorb disturbance and reorganize so as to retain essentially the same function, structure, and feedbacks – to have the same identity*" [5].

In summary, many systems rely on 1. The capacity to anticipate, detect and absorb the disturbance, 2. The capability to reorganize, and 3. The capacity for learning and improvement.

A. The Task Force Definition of Resilience

The resilience-oriented enablers within the power system can be classified by considering the time of the event's occurrence as shown in Fig. 1, where resilience features that apply before the event enable anticipation of the extreme event and preparation for it. During the event, the basic feature is the absorption,

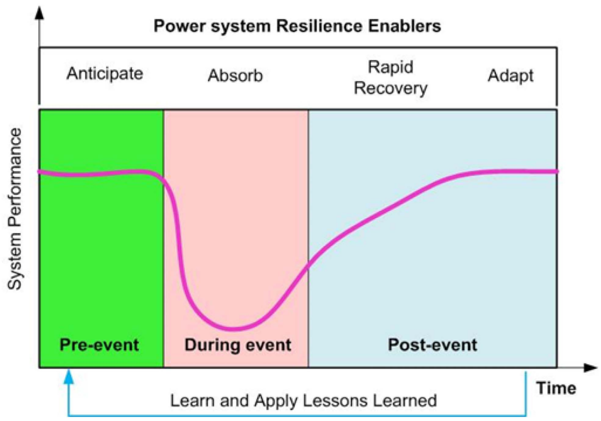

Fig. 1. The mapping of basic resilience enablers (features) to the event-relative periods.

while after the event (post-event period) rapid recovery is a key resilience feature, followed by the adaptation and learning features, which enable resilience enhancement based on the lessons learned from the past extreme events.

In light of the same (or strongly overlapping) objectives, the similarities and differences with definitions of resilience proposed by CIGRE, FERC, and other government and industry bodies, this task force proposes the following definition [6]: "*Power system resilience is the ability to limit the extent, system impact, and duration of degradation in order to sustain critical services following an extraordinary event. Key enablers for a resilient response include the capacity to anticipate, absorb, rapidly recover from, adapt to, and learn from such an event. Extraordinary events for the power system may be caused by natural threats, accidents, equipment failures, and deliberate physical or cyber-attacks*."

In line with the proposed definition of power system resilience, several conceptual frameworks have been developed. These frameworks aim to highlight the key features (i.e., absorptive, adaptive, and recovery) across the time span of a triggering resilience event. For example, it is possible to group the capabilities for withstanding, surviving, and recovering before (B), during (D), and after (A) an extreme event, respectively. These features might include anticipation (B), preparation (B), absorption (D), adaptation to sustain critical system operation (D, A), power system restoration (D, A), learning (A), and improvement (A), as detailed in Fig. 2

It is also possible to group the capabilities in the feed-forward path (anticipation, preparation, absorption, adaptation, and restoration/recovery) and the feedback path (adaptation and learning). This feedback structure of resilience (as shown in Fig. 1) was clearly outlined in [7].

B. Multiscale Aspects – Temporal Stages and Spatial Domains

To obtain more detailed insight into the resilience enablers/features, tasks, and measures (activities) from the temporal standpoint we propose a unified version in Fig. 2.

Tasks differentiate between planning and operation, measures (activities) list different types of responses while allowing some overlaps, and stages feature coarse (pre-, during- and after-event) and fine grain descriptions:

1) "Short-term" "Pre-Event Prevent" phase on an hourly basis before the event is present, typically, in case of meteorological events.
2) "During-Event Detect" and "Resist" phases are again appropriate for meteorological disturbances; however, their duration can be very short in case of earthquakes and malicious attacks.
3) "During Event" stage is appropriate for a single disturbance event and it does not cover multiple (meteorological) events whereby restoration starts before the second impact, etc.
4) There is no further system degradation in the "During-event Adapt" phase.
5) The "Downward" performance curve is an approximation of the step-wise downward curve. Possible performance improvements by automatic controls are not taken into account.
6) The "Upward" performance curve in the "Post-Event Restore" phase does not consider human errors, which are often experienced. The temporal classification does not recognize regulatory aspects which are reported to the Regulator.
7) Although the temporal evolution in Fig. 2 resembles resilience trapezoids for planning and operation tasks, it identifies not just feed-forward and feed-back features but identifies a difference between infrastructure and services provided by the power system.

Useful temporal classifications of tasks/measures are:

- Resilience orientated planning: Longer-term task, not focused on a particular event but a class of possible events (such as vegetation management, operational training, and acquisition of strategic reserves).
- Preventive response: Short-term activities to prepare for a particular predicted event.
- Emergency response: Activities during or following an event (such as network reconfiguration, activation of reserves, provisional resupply, preliminary repairs).
- Power system service restoration: Activities aimed at re-energizing all parts of the network.
- Power system infrastructure recovery: Restoration and rebuilding of infrastructure.
- Learning from events, with the goal to enhance system resilience and improve system performance (which is, again, resilience-oriented planning. Therefore: "prevent" = "post-event") and on a finer timescale in the course of an event. It is in the feedback path and same as Adapt/Learn in Fig. 1.
- Resistance: The power system resists the event (e.g., via redundancies, reserves hardened equipment, etc.); supplied level of service is not yet degraded.
- Absorption: Extreme event consequences are contained via emergency measures; supplied level of service might be degraded.
- Adaptation: Flexibilities are exploited to minimize extreme event consequences.

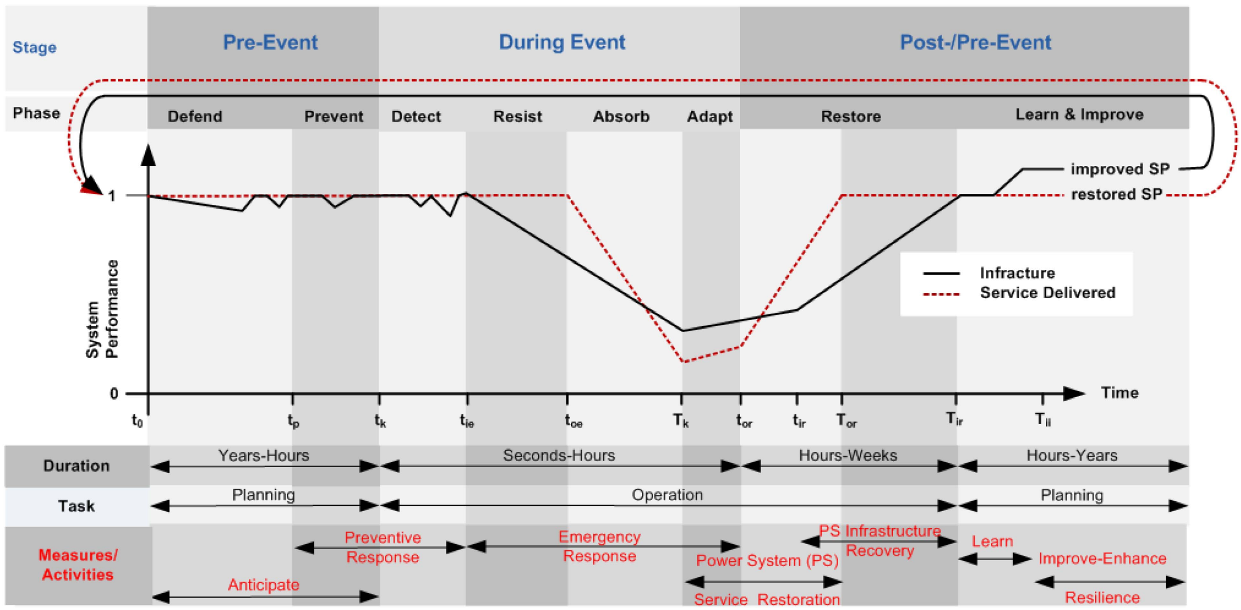

Fig. 2. Temporal classifications of resilience-oriented planning and operation actions and measures, based on [8], [9], [10], [11]. "Pre-, During and Post-Event" refer to the "extreme adverse event" in the sense of the definition above.

- Power system Service Restoration: Most critical grid infrastructure is reenergized, customers are resupplied, service is restored (not necessarily via the full infrastructure).
- Infrastructure Restoration (Recovery): all facilities, services, and personnel are brought back to normal operation.

Not all events and temporal classifications are meaningful for every resilience incident (e.g., there might be no prediction of an event such as a cyber-attack) and the order of events is not strictly fixed (e.g., damage can be first detected before or after the delivered service level starts degrading).

Our definition does not distinguish between external and internal events, as this delineation may be hard to establish in all cases; nevertheless, it may prove useful in some analyses. Furthermore, there are two distinct perspectives on the power system performance, exemplified by the red/dotted line and the black/solid line in Fig. 2:

- Customer/external perspective (service delivered): For the power system, this metric encompasses the extent and quality of the supply of all customers.
- Operator/internal perspective (infrastructure): This metric includes all capabilities that are available to the system operator, including redundancies, reserves, measurements, etc.

In a system equipped with redundancy and reserves, the power system performance from the internal perspective can be severely degraded before there is any degradation of performance from the external perspective. This distinction is particularly relevant for interconnected infrastructures.

C. Pre-Disturbance: Planning and Preventive Aspects of Resilience

Planning and operation are fundamental activities for effective power system functioning. Planning measures allow the development of power systems by addressing technical, economic, environmental, and social needs. Preventive measures aim to allocate resources to assure its adequate operation.

Traditionally implemented measures, driven by decades of experience, are security and reliability-oriented, and need to be revised to provide adequate resilience. It is conceivable that the operating modes (or security-related states) [12] of a power system may greatly amplify the impact of an external event. Resilient systems must, therefore, be equipped with appropriate intelligence for leveraging the signals coming from widespread sensors and making sense of them in the identification of these pattern changes [13].

1) Planning Measures – Long Term: The planning activities are fundamental to power system enhancement since they drive the grid development by considering the evolution of several aspects over time, such as reinforcement, replacement, and new connections of components to address load growth, aging components, increases in renewable energy penetration, need to make the grid smarter by deploying new technologies and sensors.

The traditional planning activities are security- and reliability-oriented, which focus on routine events that occur repeatedly in time. For these reasons, traditional planning measures need to be revised to effectively provide system resilience. The task is made more challenging by deregulation and by the increasing reliance on ICT. Given that the owners and regulating authorities for generation, transmission, and distribution assets may differ, they usually develop projects independently. Furthermore, interconnected power systems can include numerous nations with different regulatory environments and incentives.

Hardening-based (so-called "hard") approaches include infrastructural and technological measures aimed at strengthening the power system against extreme events [8]. They include: a) vegetation management and trimming around the grid components; b) overhead lines replacement with underground cables; c) new lines installation; d) component reinforcement (substations, poles, etc.); e) promotion of distributed energy resources (DER) in distribution grids along with the capability for island/microgrid capability [14], [15].

In contrast, algorithmic (so-called "soft") approaches concern all strategies make the system smarter and more controllable such as a) employment of load/DERs control strategies; b) adoption of distributed monitoring, estimation, and control policies.

A common practice is to map the planning task into an optimization problem, possibly with a set of scenarios to be considered. This task is made difficult by a) the uncertainty about the occurrence and intensity of extreme events and their impact on the power system; b) a large number of control variables and scenarios; c) the uncertainty in several input data, such as load and renewable sources predicted profiles; d) partial or complete lack of information about interdependent systems; and e) technicalities, such as the need to deal with mixed-integer problems [8].

2) Preventive Measures – Short Term: Resilience operational response is composed of a "preventive response," aimed at allocating resilience resources to face a possible HILP event, and an "emergency response," aimed at mitigating the extreme event effect on the system [16].

"Preventive response" aims to allocate resilience resources by considering options such as the optimized grid topology switching and/or distributed generation reserves to mitigate the HILP propagation effects on the grid. Furthermore, time-spatial forecasting tools play a crucial role in the case of weather events. While governmental meteorological offices play a key role in this domain, there is a possibility to improve the performance by integrating data-driven techniques ("Big Data"). These forecasting activities are critical in the operation of renewable sources like wind and solar [17].

The implementation of preventive resilience measures is more difficult in the case of events perceived as one-of-a-kind, such as cyber/terrorist attacks, earthquakes, and tsunamis.

D. During Disturbance: Detection and Emergency Response + Recovery

The emergency response during an extreme event (disturbance) often faces two stages in system outages – initial impact followed by a cascading stage.

Initial outage stage (within During Event stage in Fig. 2): Components fail or outage due to an extraordinary event, often in large numbers and correlated spatially [18]. The models for initial outages are local and component-based, including probabilistic models of component failure. For bad weather, there are increased probabilities of an outage. For earthquakes and high winds, there are component fragility curves that describe probabilistic outcomes in terms of components damage for a given intensity of the stressor [19]. For malicious attacks, there are presumed attacks on specific components. Stressors such as earthquakes, hurricanes, and floods have elaborate models that can be coupled to the component failure models.

Cascading outage stage (within During Event stage in Fig. 2): Cascading is the successive propagation of outages in the grid to a wider region beyond the initial outages. This may include cascading via interdependencies with other infrastructures such as ICT [20]. In rare cases, but which are also cases of substantial risk, a substantial portion of the interconnection is blacked out by cascading. Cascading is much more extensive in transmission grids than in distribution grids. The cascading outages are mostly disconnections by protection equipment due to the disrupted operating conditions rather than damaged components. When the cascading outages stop, the area of the grid that is affected is determined.

A key facet of resilience for cascading outages is that cascading is either suppressed or is shorter and more limited in extent. However, with improvements the initial outage, cascading, and restoration stages may substantially overlap in time. For example, initial outages may occur during cascading, and restoration can start while outages are still occurring [21].

E. Post-Event: Restoration and Recovery

1) Post-Emergency Near Term – Service Restoration: **Adapt and Restore phase** (within Event and Post Event stage in Fig. 2): Electric service is restored to the blackout area in transmission by successively providing additional generation and reconnecting portions of the network and load. Analogous procedures are used in distribution systems. This includes the restoration of isolated areas that cannot yet be reconnected to the bulk power system via emergency generators or other black-start-capable local generators. Furthermore, the grid may be configured in a way that is not deemed adequate for normal operation, e.g., because it conflicts with the normal market operation or creates more grid losses than usual.

The restoration activity often focuses on black-start units together with a search for feasible line switching paths that respect network constraints. Since the line switching presents a sizeable dynamic perturbation, it is necessary to consider stability implications as well.

In distribution grids, a further constraint is to assure the grid operation with an assigned topology (e.g., radial) in the presence of possible switch configurations.

2) Post-Emergency Longer-Term - Recovery: **Infrastructure Recovery** within Restoration phase (within Post Event stage in Fig. 2): When service to all customers is restored, the state of the grid can still be impaired. Properties such as N-1 security, loss-efficiency, and allocation of generation in accordance with market results are not yet necessarily restored. This state includes the repair or replacement of damaged equipment and the return from emergency to market conditions. Depending on the nature of the damage and dependencies on other infrastructure (such as ICT and transportation) and the regulatory environment, the order of the following recovery steps can differ:

- Repair of damaged equipment (e.g., lines and transformers).
- Synchronization of remaining grid islands to return to interconnected operation.
- Replacement of backup and emergency systems by the respective components that are used in normal operation.

When damaged components are not replaced by the same (or equivalent) components but by improved versions, this phase may overlap with the "Learn and Improve" phase.

F. Post-Event: Learnign and Improvement

Based on the experience gained from real-life extreme events, utilities will normally try to improve their infrastructure, as well as their planning and operational procedures, i.e. to enhance system resilience. New "realities" are introduced in operation through comprehensive training programs, with more details given in Section VIII.

IV. Relationship With Robustness, Security, and Reliability

In contrast to the definitions of robustness and resilience given in ecology [22], biology [23], or in complex systems [24], [25], which are inclusive to each other in that robustness includes resilience or vice versa, we argue that for engineered systems such as power systems, the definitions of these two concepts should be distinct from each other (with some possible overlap) so that they may become useful tools during various stages of the power system planning and operation.

Robustness is largely a scenario-independent approach to system survivability, which is embedded in component design. Restoration and recovery portions of resilience add an active, scenario-dependent component, embedded in system operating procedures and human decisions (starting with the response portion during the resilience event).

Robustness indicates the ability to withstand disturbances, while resilience includes both the ability to withstand disturbances and the ability of fast restoration and recovery. Clearly, increasing robustness is likely to help resilience. However, it may be impractical and uneconomic to bring the system to a very high level of robustness as a primary means of improving longer-term performance. Resilience is likely to be an economically more viable choice, especially when considering extreme events.

Security is a concept that has been part of power system planning and operations (including preventive and corrective actions) for many decades. In its simplest form, the N-k security considers all possible k-tuples of outaged elements, typically in a deterministic framework. This is uneconomical and impractical for k values that have been observed in resilience events (because of the combinatorial growth of the number of cases to be analyzed). This points out a need for separate scenario-based resilience studies. In such scenarios, we look for detailed recovery analysis whose parameters may differ from the ones assumed for recovery in reliability studies (which implies averaging over many smaller events). With the advent of the Internet, security has to include both physical and cyber aspects. One novel item in resilience is that it considers detailed interventions, namely specific actions by the system operator and manager, and quantifies their effects on performance.

Reliability is generally considered to have two aspects in power systems, adequacy, and operating reliability. For example, in NERC terminology: *Adequacy* is the ability of the electric system to supply the aggregate electric power and energy requirements of the electricity consumers at all times, taking into account scheduled and reasonably expected unscheduled outages of system components. This establishes a family of base configurations to be explored.

Operating reliability is the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components; it is typically studied in a stochastic framework, where there is no possibility to repair some components in the studied (short-term) time interval (for example, generating units can only fail and cannot be repaired in the 24-hour ahead planning). Operating reliability could well consider dynamic aspects of the system behavior, but that is not common today.

Among the most commonly used indices of adequacy/reliability in transmission are loss of load expectation (LOLE) and Expected Unserved Energy (EUE). LOLE is the Expected number of hours/year that a system cannot serve load, and EUE is the Expected Energy not supplied. On the other hand, the most commonly used indices in distribution are system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI).

Reliability aims to capture events that appear and re-appear with temporal regularity, like conventional outages. However, the focus changes in the case of resilience, where only exceptional (and hopefully rare) events count, and a direct comparison within resilience is only possible between events of a similar type (e.g., hurricanes) and similar intensity category (say 4). This focus on exceptions is justified in part by the economic impact, and even more by the community impact. It is thus challenging and may prove impossible to fully describe resilience events from their impact on electric power systems alone (energy lost, customers unserved, etc.).

One reason for including resilience considerations in the power system workflow is simply to complete the analysis. Resilience events typically map into "Major Event Days" or "One-off Events," with the justification that this decision prevents the reliability calculations from being skewed by extreme events that are "force majeure," and thus outside of the scope of normal operation. We argue here that this exclusion amounts to disregard for valuable information that is important in its own right, and offers additional means to understand other system abilities, like reliability, robustness, and security. It is of course possible to include some high-impact, low-probability (HILP) events in the reliability calculations via modified "Major Event Days" or "Exempt Events."

An attempt to fully include all HILP events would possibly significantly change results (and disable straightforward comparisons with historical records), while at the same time not offering sufficient resolution needed for resilience improvement. This points toward the need to perform reliability and resilience studies as separate but coordinated activities. It should be pointed out that the issue of reliability in the case of exceptional events has been recognized in the literature, for example in the case of hurricanes [26]. Since hurricanes last only a short time duration but their impact is drastic, conditional short-term or interval-based reliability indices instead of the steady-state ones are calculated [26].

It is recognized that the prevalent use of two-state weather models to compute the steady-state indices is appropriate for normal weather deviations but would downplay the effects of extreme weather like hurricanes due to the averaging effect. The

TABLE I
OVERALL SYSTEM RESILIENCE INVESTMENTS

Scheme	Investment Category	Investment Sub-Category	Triggering Metrics*	Triggering Metrics Examples
Traditional	Replacement	By Asset Types	Internal	Asset Health Index (AHI); Age of Components; Failure History
Traditional	Reinforcement	General; New Connections	Internal	N-k principle; Lost Capacity vs Outage Duration
Traditional	Reliability	By Voltage Levels	Internal	Existing/Future Automation Level
System Resilience	Extreme Weather	By Weather Events	External/Internal	Flood Probability; Tornado Category; Design Standards
System Resilience	Other Natural Disturbances	Earthquakes; Geomagnetic Volcanic	External/Internal	Earthquake Magnitude; Geomagnetic Field Variation Solar Storm Observations; Volcanic activity index; Dispersal index Fragility Curves; Design Standards
Network Resilience	Attacks	Physical; Cyber	External/Internal	Site Importance; Communication System Type Fragility Curves; Design Standards

*Triggering metrics are factors and concepts used to initiate different types of capital investments.

solution proposed is to compute conditional reliability for the interval during which the event occurs and restoration is performed. This conditional interval-based reliability may reflect some measure of resilience.

The relationship between reliability and resilience is best described as a feedback mechanism since the two activities complement and feed data into each other. The two differ at all three stages (pre, during- and post-event) with resilience during-event analysis typically being on a finer time scale. Decision paths and processes activated during resilience events are normally not exercised in day-to-day operation, thus justifying a separate study of resilience.

Portability of lessons learned: Reliability quantities are fairly directly transferable among different power systems; resilience is less so, as the extreme events may be unique and rare for proper statistical characterization. However, major classifications (hurricanes, earthquakes, etc.) are still very informative. In addition, a proper understanding of resilience includes external metrics, such as the community impact, which are nevertheless important for properly framing the workflow in an electric power system.

V. QUANTIFICATION METHODS

Resilience has a multicriterial perspective, therefore, many metrics can be associated with the resilience process, depending on the principal aims of the study, type of event, desired granularity of the analysis, etc. Similarly, of interest are characterizations that are internal to the power system, and those that relate to external systems such as other infrastructures and the society itself.

One way to organize resilience metrics is to introduce a multilevel structure in which a coarser, higher-level analysis that also connects with exogenous systems occurs at higher levels, while a finer analysis that fully utilizes data available from within the power system occurs at lower levels. The two are connected in a feedback structure where adaptation and learning related to both external and internal specifications occur at both levels (long-term feedback). In addition, at each level validation and verification of models provides "within-level" (short-term) feedback.

A. Quantifying Resilience-Enabling Investments

Power system resilience is intertwined with power system reliability (see Section VII). Thus, metrics for the two overlap in part and need to be considered in a coordinated manner. These metrics are a part of inter-system coordination (external, as in the infrastructural interdependencies) and a part of the power system's long-term and operational planning (internal).

An example of the relevant power system investments is presented in Table I. The investment categories are defined in line with legislation and regulatory setup, as well as with the identified hazards and risks.

The first three categories, replacement, reinforcement, and reliability are funded through traditional schemes. On the other hand, power system resilience investments are grouped into three relatively broad categories driven by extreme weather and other natural events (Earth-originated), geomagnetic disturbances (Space-originated), and active-adversary initiated attacks (physical or cyber) on electricity systems. Solar activities, in particular coronal mass ejections, can cause variations in the Earth's magnetic field, induce currents in transmission lines, and saturation of transformer cores, resulting in damage due to overheating [27], whilst electromagnetic pulse weapons are also a threat to power systems.

The consequences of physical attacks are studied on the national and regional levels by using scenario-based approaches, in which electricity supplies of regions/cities are provided in alternative ways. Finally, power system resilience to cyber-attacks needs to be better understood and is one of the major topics in the resilience analysis of future systems; several categories are listed in [28].

The time horizons currently covered by different planning and operational preparedness measures can go up to fifteen years [29]. Several investment categories required for the provision of overall operational preparedness are listed in Table II.

The traditional preparedness categories are classified into yearly, week-ahead, and day-ahead activities; in countries with the significantly varying impact of weather on the power system operation, there is also a seasonal planning category. Currently, it is hard to distinguish between the "traditional" and "resilience" components of workforce preparation. However, training adequate staff for the restoration of system-wide outages is probably the most important component of the latter.

Blackstart generators, which can be started without any connection to the grid, are a key element in restoring service after a widespread outage on the transmission network. At the distribution level, blackstart needs to be provided at many geographically distant locations and the blackstart capabilities are currently mainly made up of batteries, chargers, and battery savers. In countries where voltage can collapse in some regions,

TABLE II
OVERALL SYSTEM PREPAREDNESS – OPERATIONAL AND EMERGENCY PLANS

Scheme	Investment Category	Investment Sub-Category	Prepardness Metrics*	Prepardness Metrics Examples
Traditional	Week-Ahead Planning	Construction Outages Generation Reserves Hydro-Thermal Coordination	External/Internal	Operational N-k; Reserve Types and MW Hydro-Schedule
Traditional	Day-Ahead Planning	Unit Commitment Economic Dispatching Frequency Response	External/Internal	Generation MW and Bid Costs Generation Droops
Traditional/ System Resilience	Workforce Resilience	Staff Renewal; Staff Training Mental Health	External	Staff Metrics are Age; Skills; Certification
System Resilience	Black Start	Transmission & Distribution	External/Internal	Specific Black-Start Unit; Distribution Batteries Processes
System Resilience	Brown Start	Transmission & Distribution	External/Internal	Specific Brown-Start Units and Compensators Distribution Batteries; Processes
System Resilience	Emergency Plans	Attacks Weather-Related Events Cyber Attacks	External/Internal	Alternative Supplies; Staff-on-Call Weather-related metrics in Table 7.1 [6] Increased attack penetration attempts Employee disgruntlement Increased international or terrorist tensions
System Resilience	Other	New Ancillary Services Resilience Tree Cut Pandemic	External/Internal	Generation and Demand MW; Tree-line Distances Stockpiled vaccines & PPE; Medical tests Number of vaccinated employees

*Preparedness metrics are concepts, objects and factors used to invest into the operational preparedness.

brownstart needs to be funded and prepared for. Finally, there are other network preparedness categories specific to individual countries and/or regions.

B. Metrics for Stages of a Resilience Event

The rationale for considering all the stages of resilience together is that improving resilience for the benefit of society costs money that is only reluctantly invested. Effective spending requires evaluating mitigations in all stages. At each stage, there are "internal" metrics that quantify the impact on the grid that are useful for technical management of grid resilience, and "external" metrics that quantify the effect of the grid on its customers, other infrastructures, and society. Both types of metrics are important and need to be studied at each stage.

The metrics for the initial outages describe the power system components that initially fail (or the extent of their failure), and the load or customers immediately shed either deterministically or probabilistically.

The metrics for cascading describe the extent to which the cascading increases the blackout beyond the initial outages by components outaged or loads shed or describe the average propagation of cascading outages over a sample of cascades. More specifically, utilities report the following data by restoration stages: duration of the stage, the number of disconnected customers, MW on outage (or, restored), the type of outaged power components or protective devices, and the distribution system hierarchy [30]. The aggregated figures give the unreliability totals. In the case of resilience events, additional data that establish the conditions for Exempt Event status need also to be provided.

C. Coordination of Metrics

Grid Modernization Laboratory Consortium (GMLC), a partnership involving the U.S. Department of Energy (DOE) and the National Laboratories, initiated a project addressing the development of metrics to quantify the power system resilience [31]. The resilience metrics development effort combines two approaches: multi-criteria decision analysis (MCDA) and performance quantification [31]. Each of the approaches considers all phases of a resilience event, but with a different focus and level of granularity.

The MCDA-based and performance-based resilience metrics have complementary uses within many decision-making processes. For example, the integrated resource planning process used by many electric utilities to suggest and evaluate alternative system investments can be augmented to include resilience goals by using both approaches.

The MCDA approach is used as a screening process that supports the development and ranking of high-level alternatives. The two approaches lend themselves to multiple iterations within a single planning process. For example, the planner may benefit from an additional iteration that uses the MCDA approach to rank and filter design alternatives based on the planner's unique insight into how they would be utilized subject to extreme events and finally utilizes the performance-based approach to evaluate the subset of alternatives that have been identified as most promising.

D. Extracting Resilience Metrics From Utility Data

Processing utility data from historical events to obtain metrics is fundamental not only to quantify resilience and inform and motivate resilience investments but also to validate simulation and conceptual approaches. Further, metrics evaluated from the data often provide new knowledge about the resilience of the operational grid. In this section, we briefly review the processing of distribution, transmission, and generation data for quantifying resilience at the systems level.

Resilience curves are automatically extracted from distribution utility data in [21], such as the orange curve $C(t)$ shown in Fig. 3. In this real data, the outages and restores do not occur in separate successive phases of resilience (as in the

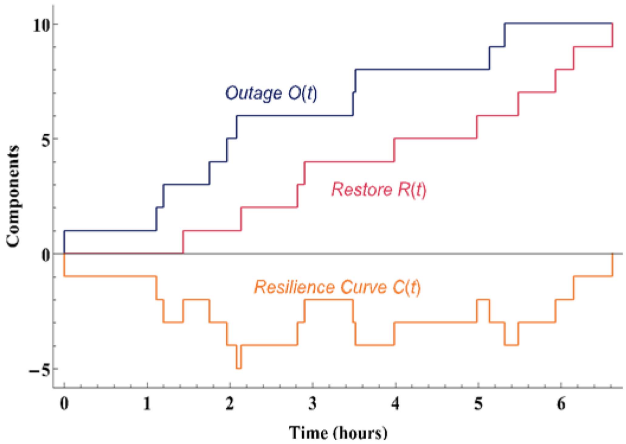

Fig. 3. The orange resilience curve $C(t)$ tracks the cumulative number of components out in real distribution data. $C(t)$ is decomposed into the outage process $O(t)$ and the restore process $R(t)$ that track the cumulative outages or restores. $O(t)$ and $R(t)$ overlap in time and enable resilience metrics to be extracted.

resilience trapezoid) but instead substantially overlap in time. Fig. 3 also shows how the resilience curve $C(t)$ can be decomposed into an outage process $O(t)$ and a restore process $R(t)$ that increase from zero to the number of outages. This decomposition can always be done, and the resilience curve $C(t)$ is simply $R(t) - O(t)$. Then metrics can be readily extracted from the outage and restore processes. This leads to formulas for the statistics of metrics such as restore durations, event durations, outage and restoration rates, and upper bounds on restoration duration. A similar decomposition works for the resilience curve that tracks the cumulative number of customers out.

In transmission systems, historical blackout data have established the heavy tails of probability distributions of blackout size that make large blackouts rare and high-risk [32]. Much of the difficulty and importance of analyzing extreme resilience events follow from their rarity and high risk. The detailed transmission line outage data collected by NERC in the North American Transmission Availability Data System (TADS) and published by the Bonneville Power Administration [33] has led to metrics quantifying the propagation of outages in blackouts such as in [34] and [35].

Resilience metrics are obtained by sampling transmission system outage data statistics in [36], and by sampling from a Markovian influence graph driven by detailed outage data in [37]. Murphy describes correlated generator outages with utility data from NERC's Generator Availability Data System (GADS) in the USA [38]. The increased generator outage rates during extremes of cold or heat and loading have a significant impact on generation adequacy. The February 2021 blackouts in Texas underline the importance of correlated generator failure data for resilience.

Significant opportunities and challenges remain for data-driven resilience metrics. Further collaborative efforts from both the research community and industry will be needed to advance data-driven resilience evaluation.

VI. Economic Aspects of Resilience

Resilience events have significant economic consequences. Some result directly from power interruptions, whereas others result from non-power system impacts. Those that can be closely linked to power interruptions are appropriate for considerations of electric power system resilience.

Interruptions of electric service have economic consequences for both the supplier and customers. For example, if power interruptions are long in duration, these consequences can include food spoilage for residential customers and losses of revenue for commercial and industrial customers.

The conventional cost-benefit analysis, in which prospective investments are evaluated by comparing the costs and benefits expressed in present-value monetary terms, is challenging to apply to resilience investments, which aim to avert the consequences of events characterized by low probability, uncertain timing, and high severity.

Resilience-focused projects are subject to the general principles of the engineering economy, but many important factors are different from privately funded projects: for example, project objectives (e.g., public health, provision/retention of services and jobs), capital sources (e.g., allowances, private lenders), multiple purposes (e.g., flooding), long project lives, and common conflicts of goals and interests [39].

The economic studies of resilience projects can be made from several viewpoints, for example, governmental bodies, utilities, and citizens; this is the first point that needs to be highlighted in any study. There are several difficulties inherent to economic studies of resilience projects, such as [39]: a) There is no measure of financial effectiveness (e.g. profit standard), exacerbated by the different levels of risk aversion of decision-makers [11]; b) the monetary measure of benefits cannot be easily identified; c) whenever public funds are used, there is a tendency towards political influence; d) there is no usual profit motive and this can have a substantial effect on project effectiveness. Nevertheless, an assessment of the resilience project benefits, or resilience project value, is still needed.

In this paper, the economic value of resilience projects is considered in terms of "avoided damage costs," or simply "damage costs." Damage costs are looked at from the customer/ public point of view and they are driven by the event's impact on society (by the consequences of the event).

A. Planning Aspects

Investments in reliability and resilience must balance the cost of providing reliable electric service with the benefits that reliable and resilient service provides to customers.

The benefits are measured by the economic consequences that customers experience when electric service is not reliable/resilient.

A formal technique for balancing (reliability) costs with benefits in order to inform power system planning was first developed by the World Bank to guide investments in greenfield vertically integrated electric power systems for developing nations [40]. The technique is now referred to as Reliability Value-Based Planning [41]. It requires two enhancements to be useful for resilience planning. First, it must explicitly account for uncertainty regarding the events it seeks to address. Second, resilience planning must account for the current sparsity of information on the customer costs of the widespread and long duration of the power interruptions that are a defining characteristic of resilience events.

B. The Economic Costs to Customers of Power Interruptions Resulting From Resilience Events

There are several methods for estimating power interruption costs to customers. Most of them were developed and are most useful in supporting planning for localized and shorter-duration power interruptions. Methods used to inform economics-based, resilience planning for widespread, long-duration power interruptions are several [42]:

Customer Survey Methods for Estimating Customer Power Interruption Costs rely on surveying statistically relevant samples of utility customers [43]. Customers are asked about the costs they would incur in hypothetical power interruption scenarios. Two distinct cost elicitation methods can be used, depending on whether the customers are non-residential or residential.

Particularly, "willingness-to-pay" asks residential customers the amount of money they would be willing to pay to avoid experiencing a particular interruption scenario. Differently, "willingness-to-accept" asks the amount they would be willing to accept as compensation for having experienced a particular interruption scenario [44]. For non-residential customers, power interruption costs, to a first approximation, are the direct economic impacts experienced by the firm whose power has been interrupted.

Revealed Preference Methods for Estimating Customer Power Interruption Costs involve reviewing what customers have actually done to prepare for and respond to power interruptions [45]. Another example is a review of premiums paid by customers for business interruption insurance [46].

Case-Study Methods for Estimating Customer Power Interruption Costs use costs that customers have, in fact, experienced as a result of an actual power interruption. The first approach involves the use of surveys of samples of customers [47]. The second approach involves applying a "top-down" analysis based on an aggregate measure of economic impact, such as the impact on the gross domestic product, to the case study.

Regional Economic Modeling Methods for Estimating Customer Power Interruption Costs is attractive because it can, in principle, capture spillover or indirect cost impacts of power interruptions, such as when an interruption disrupts the ability of one firm to make deliveries to another firm and thereby creates cost impacts on firms whose power has not have been interrupted (for more details see our Report [6]).

VII. Societal and Community Aspects

Aspects of resilience important for community resilience are investigated in various domains such as sociology, biology, policy implementation, decision-making, engineering, geography, and urban planning, among others.

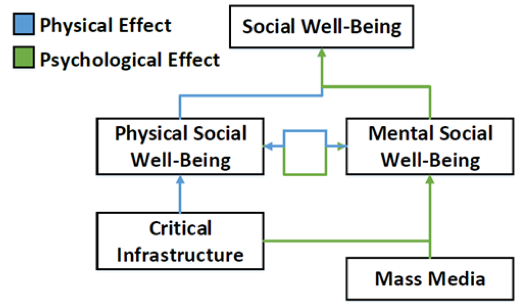

Fig. 4. Relationship between physical and mental social well-being, critical infrastructures, and mass media. Critical infrastructures influence both kinds of well-being while mass media only affects mental well-being.

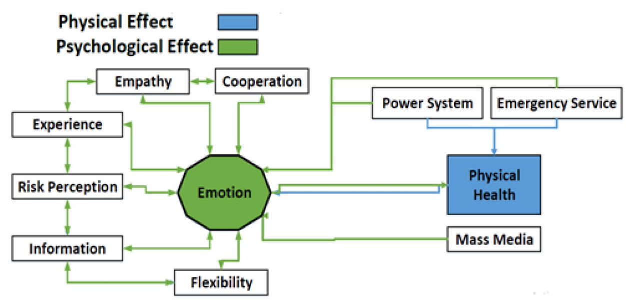

Fig. 5. The psychological and physical characteristics of a society are affected by the information provided by the emergency services and the mass media and by the accessibility to electricity. Emotion is considered to be at the heart of the proposed structure. Risk perception, cooperation, empathy, flexibility, and experience.

Community resilience is affected by critical infrastructures, mass media, and social features of the community. Critical infrastructures are of high importance for the well-being of a society [48], [49], [50]. Among them, power systems and emergency services play a pivotal role during a resilience event [51], [52]. Indeed, the availability of electric energy has a physical and emotional impact on society. Its lack can diminish physical social health due to a decrease in economic welfare and the availability of food, energy, water, transportation, and medical services, to cite a few. On-site electric generation can overcome power outages and hence, is desirable for the long-term social well-being, especially during a disaster.

Community resilience metrics quantify social physical and mental well-being. The dependence among the social physical and mental well-being and outside determinants are displayed in Fig. 4.

The development of computational models of the collective behavior of humans is instrumental for a variety of disciplines such as psychology, security management, social science, and computer science [53]. Fig. 5 displays the psychological and physical inter-dependencies among the various characteristics of a community, the critical infrastructures that serve it, and the mass media and information-seeking behavior directly influence emotion. Emotion further directly influences physical health and vice versa.

For example, if a community has already experienced hurricanes, it will be more resilient to this type of disaster than to other types. This may be considered as learning from experience and adapting to new hazards. An approach to quantify community resilience based on a multi-agent stochastic dynamical model derived from neuroscience, psychological, and social sciences is proposed in [54]. It allows the measurement of community resilience in terms of mental and physical well-being. Another community resilience optimization method subject to power flow constraints in the cyber-physical-social systems in power engineering was developed in [55].

VIII. Adaptation and Learning: Operator Training for Resilience

A. Simulator–Based Operator Training – the Present

With the technological advancement of power systems, monitoring and control systems evolved as well, requiring a higher level of operator knowledge, ability, and skills. Operator training programs today are often accredited, and operator abilities certified and periodically reassessed as required in many jurisdictions.

The basic tool used for operator training, Operator Training Simulator/Dispatcher Training Simulator (OTS/DTS), has been available for almost 40 years, having evolved through several IT-governed generations, similarly as Supervisory Control And Data Acquisition / Energy Management (SCADA/EMS) systems have developed [56], [57].

Due to economic and operational considerations, resources allocated by the utilities to the operator training and OTS/DTS maintenance are often limited. Thus, operators are mainly trained for normal and alert, so-called N-1, N-k security conditions, and also for simplified restoration tasks including black start procedure, where available and employed, but with some limitations on power system model fidelity (due to the lack of some data in case of renewables, unknown model parameters etc.).

In the context of resilience (e.g., planning, preparedness, mitigation, restoration, and recovery), Independent / Transmission System Operators (ISO/TSO) conduct system operator training, emergency management, and power system restoration activities. The key is that exercises conducted by these organizations (or like GridEx at the NERC/national level) improve resilience in at least two ways–preparedness and response/recovery. ISOs generally conduct spring preparedness drills and fall restoration drills. These exercises are based on realistic scenarios (often initiated by natural events) that cause operators to respond to and postulate recovery from disruptions to transmission system components (e.g., transmission lines and substations) in combination with major weather events that impact fuel availability (natural gas interdependency) and may also include black-start restoration response and disruptions in telecommunications.

B. New Challenges and Operator Training Requirements for Resilience Enhancement

In light of different time scales and system dynamics of the numerous processes that characterize power system resilience on the time scale from several years to weeks and from days to real-time, it is rational to separate the use of models and tools intended for simulation and training at two levels with different functionalities.

On the "upper" (tactical) decision level there are infrastructure resilience (often quasi-dynamic) simulation models and tools, whose main goal is the analysis and assessment of system behavior and response when subjected to threats and hazards.

Analysis should identify the hazards and find the initial conditions resulting from a given hazard and assess, using the infrastructure interdependency simulation models (for example, EPfast and NGfast [58]), infrastructure service outage areas, and associated technical indicators. This goal/task also corresponds to one of the components of the framework proposed in [59] and used in the utility industry.

On the "lower" (operational) decision level are operational resilience simulation and training tools, the goal of which is to simulate in more detail the impact of extreme events on system operation for defined starting conditions (highly configurable), load profile, and scenario, thus enabling not just improved understanding of consequences of these rare events and system behavior, but operator training as well.

C. Resilience Augmented Advanced Operator Training Simulator: Requirements and a Possible Architecture

An augmented advanced operator training simulator is needed for future power system operators. It needs to simulate power system conditions provoked by the extreme event typically followed by many elements of simultaneous or sequential (cascading) outages in the power system. Such an advanced OTS/DTS should have the following capabilities:

- to realistically model all relevant power system elements and devices, including power electronics;
- to represent the existing Regional Transmission Operator (RTO) / ISO / TSO information-control system at control center (like SCADA / Energy Management System (EMS), SCADA / Distribution Management System (DMS), or SCADA / Generation Management System (GMS) depending on who will be trained;
- to execute a training scenario that accommodates extreme events and their consequences on the power system;
- to represent effects and actions from other critical infrastructures (like telecommunication, gas, oil, coal, transport, water networks, etc.);
- to jointly train whole operating teams;
- to simulate disturbance development inside individual electrical islands in parallel, including cascading development;
- to be able to use several power system models with different levels of detail during the simulation, especially during restoration.

The proposed Advanced Operator Training Simulator / Advanced Dispatcher Training Simulator AOTS/ADTS architecture is shown in Fig. 6. AOTS/ADTS consists of three basic parts: power system model (PSM), control center model (CCM), and instructor's subsystem (ISS).

The power system model (PSM) within OTS/DTS should be much richer in scope to include models of system elements

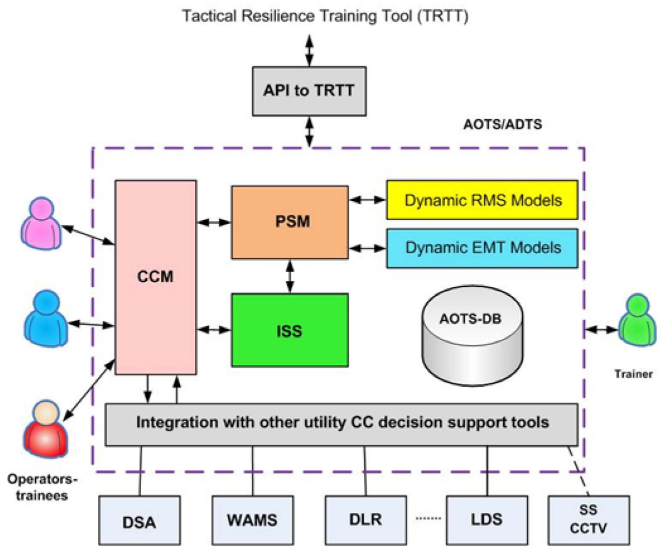

Fig. 6. Proposed architecture of the resilience augmented advanced OTS/DTS.

that emerged (like different DG/RES, storage, high voltage direct current (HVDC), etc.). Due to the possibly different time scales of interest (depending on the type of the phenomena and analysis needed) for operational resilience training, both types of models should be included, i.e., dynamic root mean square (RMS) models and dynamic electromagnetic transient (EMT) type models resulting in the hybrid dynamic simulation [60].

IX. Lessons Learned and Resilience Enhancement

Lessons learned from major resilience events have thought the industry that approaches to enhance resilience of power systems mainly fall into three categories, i.e., construction programs, maintenance measures, and smart grid techniques. These categories mirror the planning / operation / new technologies paradigm that is widely adopted in power systems.

Concerning construction programs, a straightforward way is to reinforce utility poles and overhead lines. It improves the ability of power systems to ride through high-intensity winds, heavy ice storms, and other extreme weather events.

Replacing overhead lines with underground cables is also an effective approach. Since undergrounding the entire network is costly, a better choice is to identify and underground the key components that are important for system resilience. For new power systems, construction standards should be improved by considering the impact of extreme events.

System maintenance helps to identify the devices that are close to the end of life or have a good chance of failure so that they can be replaced. Maintaining the clearance between power lines and trees reduces the possibility of tree contact with lines during a storm.

Identifying and hardening vulnerable components is also important for power sources to access critical loads during extreme events. Smart grid techniques play an increasingly important role in the enhancement of resilience of power systems, especially on the distribution level systems.

Smart grid infrastructure includes advanced metering infrastructure (AMI), remotely controlled switches/transformers/voltage regulators, telecommunications, data management, and DMS/OMS. These facilities, together with a SCADA/DMS system, enable real-time monitoring and remote control and enhance visibility and controllability of distribution systems typically down to the MV/LV substations.

Smart grid applications, such as fault location, isolation, and service restoration (FLISR), enable online analysis and improved decision-making for distribution systems. FLISR can locate and isolate the faulted zone and implement service restoration schemes as a decision support tool for distribution system operators [61].

A potential downside of the reliance on smart grid solutions is the increased reliance on the communication system which can be subjected to outages after a resilience event.

Resilience enhancement measures include planning and operational measures that can be divided into hardware- and software-dominated approaches. Among the hardware-based planning measures, elevating substations, upgrading and undergrounding existing lines, and vegetation management are commonly used in current utility programs.

In the software-based planning and operation measures, advanced metering infrastructure (AMI), remote-controlled switches/transformers/voltage regulators, telecommunications, data management, and DMS/OMS belong to smart grid infrastructures. These facilities enable real-time monitoring and remote control and enhance the visibility and controllability of distribution systems.

In restoration response measures, making use of DERs, microgrids (MGs), and networked microgrids (NMGs), to serve critical loads during extreme events contributes to resilience [62]. MGs can disconnect themselves from the grid during extreme events to serve critical loads [63], and they can support service restoration of critical loads on distribution feeders [15], [64].

With the increasing interaction and collaboration between TSOs and DSOs, new flexibility and resilience services are arising from the low voltage distribution networks.

X. Summary and Recommendations

This paper defines resilience, compares resilience with related technical concepts, and summarizes measures to enhance system resilience. Further studies are necessary to understand and quantify the interdependency of critical infrastructures.

The analysis of the literature has highlighted several key points crucial to enhance power system resilience such as:

- to investigate the cost-effectiveness of resilience measures;
- to promote cooperation between generation companies, transmission, and distribution grid operators;
- to integrate this cooperation into planning/operation methodologies to globally enhance the resilience over time;
- to enable renewable and distributed energy resources to enhance resilience;
- to develop smart grids and microgrids able to islanding;
- to employ knowledge discovery in Big Data to detect potentially dangerous conditions for the system from the acquired measures;

- to analyze the cyber-attack risks, caused by the increase in the exchange of data;
- to identify the main HILP events, given a geographic area;
- to analyze the possible HILP impact on primary source supplies such as oil, gas, and coal;
- to analyze the relationship between HILP events and power system components failures;
- to develop advanced resilience metrics and decision support approaches able to characterize the different resilience aspects;
- to develop augmented advanced system operator training simulators.

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