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Cascading Trees: A Methodology to Integrate Resiliency in Transmission Planning

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SUMMARY

The purpose of this paper is to provide a methodology to assess the probability and consequence of cascading outages. We define *cascading trees* as the set of all likely cascading paths. A *cascading path* describes a probabilistic sequence of cascading outages. The outcomes of the potential cascading paths are classified into: *bounded* (the propagation of a disturbance is confined to a certain area) and *blown-up* (the exact extent of the cascading cannot be determined). The proposed methodology is based on ac power flow and transient stability assessment. A metric of resiliency and other applications of cascading trees are described. The methodology is demonstrated in the context of PJM Interconnection.

KEYWORDS

Cascading outages, probabilistic modeling, transmission planning, resiliency.

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1. INTRODUCTION

Cascading outages are defined as "the uncontrolled successive loss of System Elements triggered by an incident at any location"[1]. Reliability has always been the main focus of power system planners, and multiple metrics (*N-1*, *N-1-1*, available transfer capability, etc.) have been implemented to ensure that the system is reliable by design and that it is operated within well-established limits. As a result, cascading outages in the Eastern Interconnection are rare. However, the consequence of large blackouts (for example, 1965, 1979, 2003, etc.) warrants the significant research efforts to model cascading outages [2-12]. These high-impact low-frequency events push the system beyond its design limits. It is argued that understanding the behavior of cascading outages can help PJM plan and operate the power system with a focus on *resiliency* (complementing the traditional focus on *reliability*).

Fig. 1 shows the potential progressions of system states as a direct consequence of an initial *N-k* disturbance. The initial event is defined as an *N-k* contingency to emphasize that the first incident may involve more than one system element (as opposed to the traditional *N-1*). If the system survives the initial *N-k* contingency, it will be in a pseudo-stable condition. If no cascading occurs, the system is classified as stable. On the other hand, if the initial disturbance causes severe overloads and/or under/over voltages, there is a chance that an element will fail/trip, leading to a cascading sequence of events. For the purpose of this research, we are concerned with cascading outages that evolve slowly (in the range of several minutes). However, as shown in Fig. 1, certain *N-k* contingencies may lead to a fast collapse of the network.

Let us classify the final state of a cascading outage into: *bounded* or *blown-up*. The final state is said to be *bounded*, if the propagation of the disturbance is confined to a certain area. On the other hand, if it is not possible to determine the extent of the cascade, the final state is classified as *blown-up*.

In general, there are multiple ways in which an initial *N-k* disturbance can be propagated. In this paper, we define a *cascading path* as a probabilistic sequence of cascading outages. A *cascading tree* describes the set of all likely cascading paths. In a nutshell, the proposed methodology consists in enumerating and quantifying the probability of all likely cascading events given an initial *N-k* disturbance.

This paper is organized as follows. Section 2 describes a methodology based on cascading trees. Applications, in the context of power system resiliency, are presented in Section 3. Final remarks and conclusions are presented Section 4.

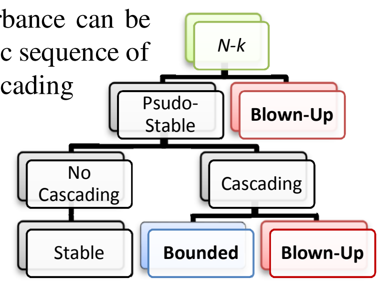


Fig. 1. Progression of system states given an initial *N-k* contingency.

2. CASCADING TREES

2.1 Overview of Cascading Trees

Fig. 2 shows a large cascading tree. Each node in the tree represents a unique system state. The numbers on the branches describe the probability of that particular cascading outage. The diameter of the terminal nodes represents the probability of each cascading path (a larger diameter indicates a higher probability of ending up in that system state). The color of the terminal nodes indicates the final outcome of the cascading sequence of events: (a) Blue terminal nodes indicate a bounded state, (b) Orange terminal nodes also indicate a *bounded* state, but the power flow solution did not reach the mismatch tolerance threshold, (c) Red terminal nodes indicate a *blown-up* state, (d) Pink terminal nodes indicate a low probability cascading paths. The threshold for low probability is user settable; in this paper, the threshold is 0.1%.

Different cascading paths can lead to the same node in the tree (for example, paths between nodes 0-2-17 and 0-4-17; each path has its own probability of occurring). It is interesting to note that a single cascading tree can have bounded and blown-up terminal nodes (see Fig. 2). Given the same initial *N-k* event, there is some chance that cascading outages will be confined to a region (bounded (blue)) and some chance they won't (blown-up (red)). At first glance, the distinction between bounded and blown-up cascading might seem trivial, but it plays a major role in the context of power system resiliency. A resilient power system is not necessarily a system where cascading does not occur, but a system where cascading is always bounded to an acceptable region.

Another feature of cascading outages described in Fig. 2 is the *avalanche* or *chain reaction* effect. One outage may cause overloads on a few lines, tripping any of these lines leads to further overloaded lines, and so on. This effect can be observed in the expanding branches of the cascading tree.

Finally, another interesting feature is that of preferred directions of cascading. The outages in a cascading path are all correlated (since the cascading probability is a function of the system state). The first cascading outage can play a major role in determining the direction of propagation; branches in the same direction have non-zero probability while branches in different directions will not materialize. It is emphasized that the branches in the trees do not represent geographical proximity.

The metric presented to planers/operators is the total probability of ending up in a bounded and/or blown-up terminal node and the expected generation/load loss. The total probability of cascading is calculated considering all cascading paths between the root node (i.e., after the *N-k* contingency) and each terminal node. Other factors like the criticality of load/generation lost and time-to-restoration can also be considered as a weight in the risk assessment.

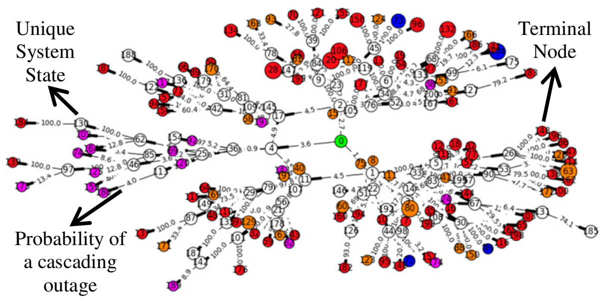


Fig. 2. Example of a cascading tree. Terminal nodes are color coded: blown-up (red), bounded (blue and orange), low probability (pink).

2.2 Cascading Propagating Mechanisms

The cascading propagating mechanisms are described by a mapping function between an element exceeding its operating limit and its perceived probability of failing/tripping. The key assumption is that there is relationship between the prevailing system conditions and the probability of materializing a cascading outage.

These probabilities are heuristically defined based on the expertise of asset owners and should not be interpreted in the sense of a frequentist approach. There is an expectation (based on operating experience) that higher exceedances lead to higher chances of tripping, but such relationship has not been statistically quantified.

The following cascading propagating mechanisms are considered in the algorithm: (a) Transmission line overloads: describes the relationship between an overloaded line and its probability of tripping. Thermal overloads tend to expose weaknesses of transmission lines: splices, line sag and critical clearance, power line carrier filter, etc., (b) Transmission line protection: describes the relationship between apparent impedance seen by the relay and the probability of materializing a hidden failure [13]. Protection system hidden failures have played a major role in cascading blackouts [14-16], (c) Transformer overloads: describes the relationship between an overloaded transformer and its probability of tripping. The probability curve is designed considering the thermal time constants associated with active and structural parts of transformers, (d) Generators: describes the relationship between low-voltage at the generator and its probability of tripping (over/under excitation, auxiliary equipment, etc). In particular, nuclear plants auxiliary equipment is sensitive to sustained low voltage (for example, April 27, 2015 PEPCO event [17]).

Fig. 3 shows an example of a probability mapping function for transmission line overloads. The x-axis shows the line loading expressed as a percentage of rate B (emergency overload). An overload greater than 150% of rate B has a probability of 1 of tripping; i.e., it is implicitly assumed that, due to the severity of the overload, corrective actions cannot be implemented in time to avoid the cascading of that line. The shape of this curve is user settable; PJM uses slight modifications of this curve based on the transmission owner's input.

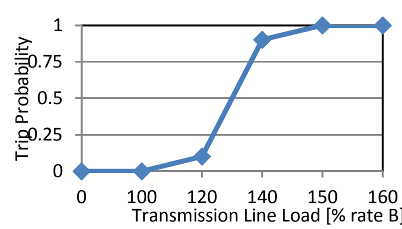


Fig. 3. Probability mapping for transmission line thermal overload. Examples of mapping functions for system protection, transformers, and generators can be found in the Appendix.

Other cascading analysis methods use a similar threshold-to-trip approach [2, 4, 10, 18]. However, a step-change mapping function is typically used to described such threshold. That is to say, at values higher than 150% the line trips, but at 149% it does not. It is argued that the *continuous probability* reflects more accurately the physical behavior of cascading, and allows us to track the total probability of a cascading path.

2.3 Operator Corrective Actions

The evolution of a wide-spread outage can range from a few minutes (2011 Southwest blackout [19]), to more than an hour (2003 Northeast blackout [20]). It is estimated that 50% of blackouts have a slow progression, allowing for operator remedial actions [10].

The following corrective actions are considered at every cascading step to mitigate transmission line and transformer overloads, and system under/over voltages: a) Re-dispatching generation, b) Load shedding, c) Switched elements (capacitors, reactors), d) Transformer tap-changers, e) Topology control (pre-studied switching solutions).

A heuristic rule is then used to *assess the feasibility* of the corrective actions. If any amount of generation re-dispatch and load shed is allowed, all violations can theoretically be mitigated. A corrective action is feasible if it is reasonable to expect an operator to execute it in a timely fashion before the next cascading event. For example, re-dispatching 5 GW of generation and shedding 1 GW of load may alleviate all system violations. However, it is unlikely that an operator will be able to accomplish such maneuvers in a short period of time, especially during stressed conditions.

If the corrective actions are deemed feasible, they are implemented and the probabilities of cascading are re-calculated; the probabilities remain unaltered, otherwise. The limits selected for this paper are shown in the Appendix.

2.4 Power Flow Convergence: Hard Solution

Cascading trees are grown using ac power flow solutions. Due to the severity of the initiating event (*N-k*) and subsequent cascading outages, special care is needed to guarantee that a diverging solution truly indicates the lack of an operating state (rather than a mathematical issue associated with the Newton-Raphson algorithm).

The ability to converge to a solution (provided that it exists) is a function of the distance between the pre/post-contingency system states. A suite of Python™ programs, called *hard solution*, was developed to slowly transition from one system state to another. Given any contingency, rather than disconnecting all elements at once (transformers, lines, generators, etc), the following sequence of steps is taken: 1) Load is "ramped down"; i.e., load is decreased in a series of steps (at each step, a power flow solution is calculated), 2) Capacitor banks are ramped down, 3) Generators are ramped down. Re-dispatching may be necessary depending on the amount of generation lost, 4) Transmission lines are "faded away". The transmission line is replaced by real/reactive power P-Q injections at both terminal buses. These P-Q injections are ramped down. In essence, this algorithm improves the chances of convergence of the power flow at the expense of computational time (1 power flow solution is replaced by $m*n$ solutions, where m is the number of elements in the contingency and n is the number of steps in which the elements are faded away).

Fig. 4 shows the resulting sequence of voltage contours (a)-to-(f) as a particular transmission line (highlighted in the figure) is being faded away by the *hard solution* algorithm. The general deterioration of the voltage profile as the power flowing through the line is being chocked is enlightening. It is clear that the solution diverges due to a voltage collapse (as opposed to a mathematical issue). The *hard solution* algorithm takes us as close to the point of collapse as possible (Fig. 4 – (e)). In the next step (Fig. 4 – (f)), when line is "fully disconnected", the system voltage collapses.

Fig. 5 shows an example of a bounded cascade. In this example, each voltage contour (a)-to-(f) represents a different cascading outage. Note that voltage is extremely depressed in certain areas of the network (Fig. 5 – (e)); as low as 0.54 pu. After the final outage (Fig. 5 – (f)), there is a blackout in a portion of the network (white region), but the rest of the system is healthy and there is a zero chance of another cascading outage (i.e., bounded cascading outcome). Interestingly, bounded cascading is not given much attention in previous publications, yet most of our operating experience is precisely with bounded cascading outages (a few sequence of events that impact a defined region).

As a final remark, the amount of load/generation loss for bounded cascading can be quantified (white region in

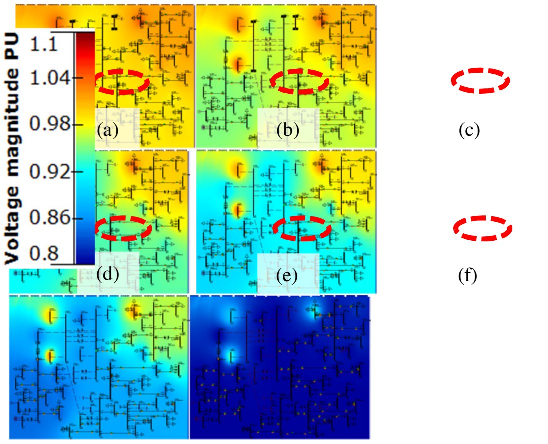


Fig. 4. Example of a blown-up terminal node. As the transmission line is "faded away", voltage deteriorates across the system until it finally collapses; sequence (a) through (f). The hard solution algorithm confirms this is not a mathematical problem; there is truly no stable operating state.

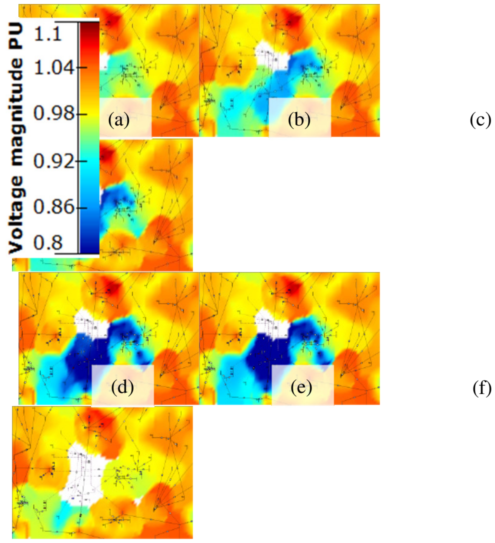


Fig. 5. Example of a bounded cascading path. The sequence of cascading events (a)-(f) shows the deterioration of the voltage profile and subsequent blackout of a defined area. In the final system state (f), the rest of the system is healthy and there is no element likely to cascade; i.e., the cascading is confined to a defined region.

Fig. 5 (f)). On the other hand, it is not possible to quantify the exact load/generation loss for blown-up cases. The last valid solution (Fig. 4 (e)) is used to estimate load/generation at risk using a heuristic rule. Load connected to a bus which voltage is less than 0.8 pu is determined to be at risk.

3. POWER SYSTEM RESILIENCY IN THE CONTEXT OF CASCADING TREES

3.1 NERC CIP-014

The proposed methodology was originally designed to address NERC's CIP-014 Physical Security standard. The standard requires transmission owners to identify and protect facilities that if rendered inoperable could result in "instability, uncontrolled separation, or Cascading within an Interconnection" [27]. Dominion Virginia Power (a PJM transmission owner) has utilized the proposed methodology to identify and rank critical substations. The initial *N-k* event consists on the complete loss of a substation. Cascading trees quantify the probability of cascading and its associated consequence (blown-up vs. bounded, load/generation loss), leading to a natural ranking of substations. Based on this ranking, substations were grouped into different tiers; each tier has a different priority and a different set of mitigation actions.

3.2 Transmission Planning for Resiliency

The best way to protect a critical substation is not to have a critical substation. PJM is currently developing a metric of resiliency to complement and enhance a planning process which has traditionally been focused on reliability and efficiency.

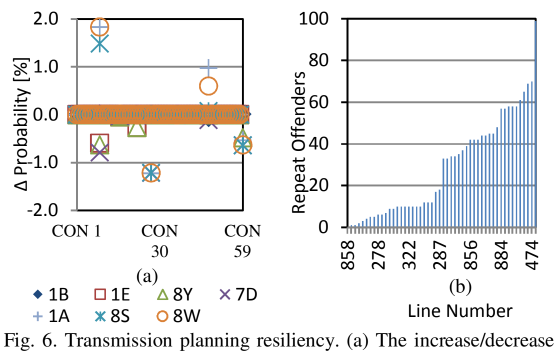


Fig. 6. Transmission planning resiliency. (a) The increase/decrease on cascading probability can be used as a metric of resiliency to compare projects submitted to PJM through FERC Order-1000. (b) Transmission lines that show-up frequently across different cascading paths. These "repeat offenders" highlight potential corridors to improve system resiliency.

The intent is to incorporate cascading trees as a weighting factor in the metric of resiliency. Intuitively, projects that reduce the probability or extent of cascading, or that increase the chances of a bounded cascading (i.e., going from blown-up to bounded), make the system more *resilient*. As an example, Fig. 6 (a) shows a comparison of different projects submitted through PJM's FERC Order-1000 process. The y-axis depicts the difference in probability of cascading (negative numbers means the probability of cascading decreases if the project is implemented). It can be seen that some projects increase the probability of cascading (i.e., a detrimental impact on resiliency). Projects that reduce the probability of cascading would receive a better score in the selection process (other parameters like cost, constructability, performance, etc., are taken into account in the final selection of a project).

The cascading trees methodology also provides "situational awareness for planning". For example, Fig. 6 (b) shows transmission lines that appear frequently across several cascading paths. These "repeat offenders" highlight transmission corridors that are good candidates for planning projects to improve system resiliency. Fig. 7 shows the evolution of a cascading tree (and total probability of cascading) as the most frequent repeat offender is hardened (reconducting, upgrade in system protection, wave trap, etc). With just two projects the probability of cascading is reduced from 99% to 55%. Note that the size of the cascading tree is significantly reduced.

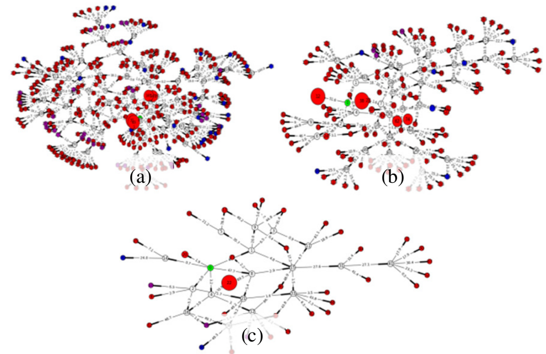


Fig. 7. Evolutions of cascading trees after enhancing the most frequent "repeat offender": a) 99% probability of cascading, b) 95%, c) 55%.

3.3 Real-Time Cascading Analysis

PJM is developing a real-time version of cascading trees to assist operators during stressed system conditions. In early 2016, an N-4 contingency put the system in a N-1 insecure state. The system had no limit violations, but a subsequent N-1 contingency led to severe overloads (exceeding 150% of rate B). PJM's current procedures requires the operator to study the subsequent outage of any lines exceeding 115% Load Dump rating (i.e., studying N-1-1, N-1-1-1, etc., up to 5 contingencies [18]). When the reliability engineer disconnected the overloaded transmission line (N-1-1), the power flow did not converge. At this point, mitigation actions were taken to return to an N-1 secured state: 8 generators in the area were re-dispatched and the system topology was changed (a bus was split).

This event was studied using the proposed methodology; Fig. 8 shows the resulting cascading tree. The "*hard solution*" algorithm was not only able to solve the contingency that previously did not converge, but also uncovered multiple alternative cascading paths (see Fig. 8). Overall, the cascading probability was 49.2% with 2.7 GW of load at risk (see Fig. 9). Incorporating the corrective actions taken by PJM's operators reduced the probability to 0%.

Operators took the right actions to ensure system reliability. However, operators emphasized the need for better tools to analyze these extreme stressed conditions. Currently, engineering judgment must be used to determine the extent of the impacted area (the lack of a power flow solution adds an extra level of complexity). PJM's operators commented that the size of the area at risk was an eye-opening result (confirming that it is not easy to intuitively estimate the extent of a cascading blackout).

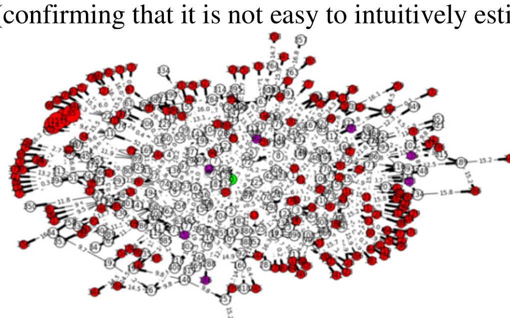
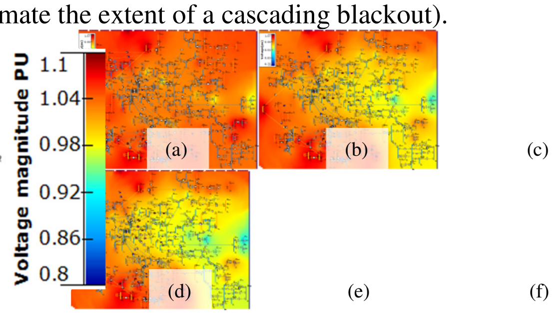


Fig. 8. Cascading tree: a disturbance put PJM in an N-1 insecure state.



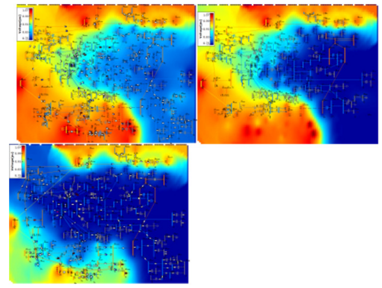


Fig. 9. Most likely blown-up cascading path after a disturbance put PJM in a N-1 insecure state. The figure shows the deterioration of voltage profile through a sequence of cascading outages (a)-(f).

3.4 Topology Control

A cascading tree can have both bounded and blown-up terminal nodes. This means that, just by chance, the impact for the same initiating *N-k* contingency may be contained within a well-defined area or not. As an example, Fig. 10 shows a blown-up (a) and a bounded (b) cascading outcome given the same initiating event. The only difference between them is that in the blown- up case, a key transmission line (highlighted in Fig. 10) remains connected during the sequence of cascading outages, pulling down the rest of the system to a voltage collapse. On the other hand, in the bounded case that transmission line tripped during the sequence of outages (Fig. 10 (b)). A portion of the system still ends up in a blackout, but the rest of the system is healthy and there is 0% probability of further cascading (by definition, bounded).

This is very interesting result; a slightly different sequence of events can lead to drastically different consequences. Further research is needed to recognize uncontrolled cascading with impending system collapse, and to determine if topology control actions can surgically reconfigure the system to improve resiliency.

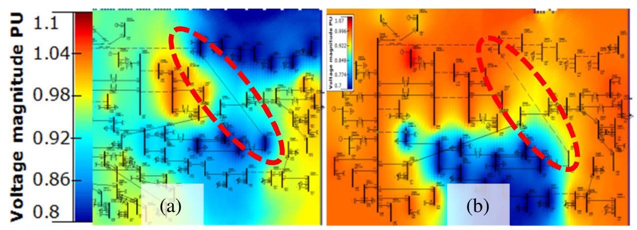


Fig. 10. Examples of blown-up (a) and bounded (b) cascading paths in the same region of the system. The example shows that topology control could prevent uncontrolled cascading and lead to bounded cascading paths.

4. CONCLUSION

The purpose of this paper is to analyze the characteristics of cascading outages, assess their probability, and determine the impact on power systems resiliency. The methodology is demonstrated in the context of PJM's grid, taking into account its intrinsic characteristics and design philosophy.

Main conclusions and final remarks are summarized below:

- Cascading trees characterize all likely cascading paths.
- The probability of a cascading outage is defined heuristically based on the operating experience of asset owners. It is a function of prevailing system violations and it is characterized using continuous mapping functions.
- If the propagation of the disturbance is confined to a certain area, the cascading path is classified as *bounded*. If it is not possible to determine the extent of the cascade, the final state is classified as *blown-up*.
- The main cascading propagating mechanisms are contemplated in the analysis: transmission line thermal overloads, protection system hidden failures, transformer thermal overloads, and generator bus voltage.
- Cascading trees illustrate some of the features of cascading outages: avalanche effect, dependence of subsequent outages, preferred direction of propagation, and the possibility of having bounded and blown-up terminal nodes (given the same initial *N-k* event).
- For extreme *N-k* contingencies, the *hard solution* algorithm minimizes the chances of having a divergent solution due to a mathematical problem. If a solution is classified as *blown-up*, we are confident there is truly no valid operating state.
- Operator corrective actions, if feasible, can reduce the probability of cascading.

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