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POWER SYSTEM RESILIENCE THROUGH THE LENS OF REGISTERED FAILURES IN THE ROMANIAN GRID

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This paper explores the concept of resilience in power systems, focusing on failures in the Romanian power grid. It examines strategies for anticipating, preparing for, minimizing, and mitigating the effects of extreme events. The paper highlights personal contributions in evaluating failures in the Romanian Transmission System Operator's lines, as well as recent developments in resilience, and suggests measures to strengthen the power system. The approach includes defining resilience, assessing system performance, and exploring technologies to enhance it, offering valuable insights for both academic and practical applications.

Keywords: resilience, power system, power lines, extreme events, failures, causes, mitigation measures, grid enhancement, technological innovations

1. Introduction

Power systems play a vital role in the functioning of modern societies. They are responsible for supplying and distributing electricity to consumers, powering buildings, industries, transportation, and critical infrastructure. However, these systems face significant challenges both presently and in the future. Ensuring the resilience and reliability of power systems is crucial for sustaining the needs of our increasingly interconnected and energy dependent society [1] [2].

Power system resilience is critical for maintaining a consistent electricity supply, especially during crises like natural disasters or technical breakdowns. Most power interruptions are caused by physical damage to a localized section of the distribution system due to weather, accidents, or the failure of aging equipment. Less commonly, outages can occur across the entirely power system due to major storms, natural disasters, operational errors, or malicious human activities [2].

The article aims to list recorded disruptions in the Romanian power system and determine their causes. It seeks to enhance understanding of system resilience, develop strategies to predict and manage disruptions, and find solutions for recovery. The main goals are to define resilience, identify weaknesses, analyze

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system performance during critical disruptions, explore improvement technologies, and suggest future research directions.

2. Defining Resilience

One of the first attempts for *defining resilience* comes from C. S. Holling in 1973 for ecological systems, where it was described as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables” [3].

Within the context of the power systems, various definitions have arisen, all emphasizing the system capability to handle disturbances. The U.S. Presidential Policy Directives-21 (PPD-21) defines resilience as “*the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions*” [4]. According to the U.K. Cabinet Office, resilience is the ability to “*anticipate, absorb, adapt to and/or rapidly recover from a disruptive event*” [5]. The United Nations Office for Disaster Reduction (UNISDR) defines resilience as [6]: “*the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions*.”

There are many ways to define power system resilience, they all share the same basic idea: resilience is about how well the system performs during and after an extreme event happened. According to M. Panteli, most definitions highlight the “***system's ability to anticipate, absorb, and quickly recover from external, high-impact, low-probability shocks***” [7].

The resilience curve shown in Fig. 1 illustrates how resilience levels change over time during a disturbance. This figure highlights the key features of a resilient system, marked by the green line, which can manage disruptions more effectively than a conventional system, represented by the red line, during extreme events like a heavy storm. Before the event at t_1, the power system must be strong and resistant to withstand the initial impact. After the event, the system enters a degraded state, with its resilience significantly compromised, as shown by the green line. For example, between t_0 and t_1, advanced weather forecasting and decision-support tools can help the system anticipate and prepare for potential challenges. From t_1 to t_2, the system can better defend against disasters through fortification. Between t_2 and t_3, the system can respond and adapt by efficiently allocating resources. Finally, cutting-edge restoration methods can be quickly applied to restore the system to near-normal operation [8].

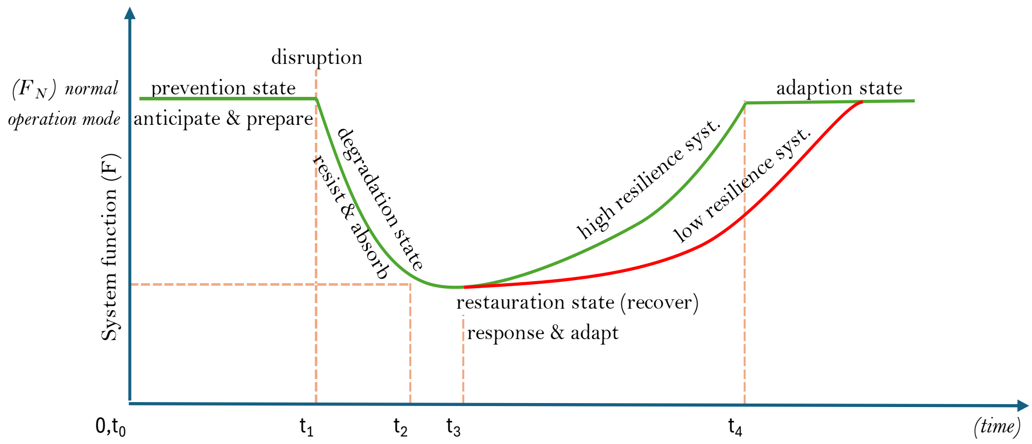

Fig. 1 Illustrative process of a resilient power system through extreme event

From another perspective, resilience comes as a completion to reliability criteria of design power systems. While reliability is about preventing failures and ensuring smooth operation under normal conditions, resilience focuses on handling problems, adapting to changes, and quickly fixing things after unexpected events. The key difference is that reliability keeps everything running smoothly, while resilience helps recover quickly when things go wrong.

3. Evaluating the Resilience Frameworks of Power Systems

Aligned with the defined concept of *power system resilience*, multiple conceptual frameworks have been introduced. These frameworks are designed to underscore principal attributes like absorption, adaptation, and recovery throughout the duration of a resilience-triggering event. For instance, capabilities can be categorized based on their relevance before (Phase I), during (Phase II), or after (Phase III) a major event. Such attributes may encompass *anticipation and preparation (Phase I)*, *absorption (Phase II)*, adjustments to maintain essential system functioning (Phase I, II), *power system restauration (Phase III)*, learning from the experience, and enhancement [9].

Phase I: Strategic Planning and Preventing Measures for Resilience and for a power system to operate effectively, strategic planning and timely operational interventions are essential. Such planning ensures the system's evolution by catering to technical, financial, environmental, and societal requirements. Meanwhile, preventive interventions focus on resource allocation to ensure smooth operations.

Historically, the measures in place have been rooted in security and reliability, this need to be revised to provide adequate resilience. However, with the realization that a power system's operational modes [10] can amplify the effects of external event, there is a need to recalibrate these measures to enhance resilience. This calls for resilient systems equipped with sophisticated intelligence capable of leveraging and interpreting signals from numerous sensors and recognizing shifting patterns [11].

Long-Term Planning Measures stands at the heart of power system improvements is the planning phase, which steers the network's growth. This includes attending to areas like infrastructure enhancement, component updates, and establishing connections that meets the rising demands, older infrastructure, increasing renewable energy integrations, and the incorporation of the latest technological advances and monitoring tools.

Traditional planning, centered on security and reliability, often focuses on recurring events. The growing need for resilience means these traditional strategies require an overhaul, especially with the complications introduced by opening and the growing dependence on Information and Communication Technology (ICT). Additionally, regulatory oversight in areas such as generation, transmission, and distribution, combined with the challenges of coordinating international power systems with differing regulations, introduces additional layers of complexity.

Reinforcement measures, termed as *"hard" approaches*, encompass infrastructure and technological steps to make the system more resistant to severe incidents [12]. This can involve transitioning from overhead to underground cables, introducing new transmission lines, reinforcing components like substations and towers/poles, and promoting the incorporation of distributed energy resources, ensuring they are equipped for islanding or microgrid operations.

On the other hand, *"soft"* or algorithmic *approaches* target making the system smarter and more manageable. This includes managing load and distributed energy resources, and the implementation of distributed monitoring and control strategies.

The planning process often translates into optimization challenges, considering multiple scenarios. These challenges arise from uncertainties about extreme events and their impacts, control variable and scenario multiplicity, fluctuating input data like predicted energy load profiles, potential gaps in information on interlinked systems, and the technical complexities of dealing with certain mixed problems [12].

Short-Term Preventive Measures for resilience operational response encompasses two aspects: a "preventive response," focusing on resource allocation to handle potential high-impact, low-probability events (HILF), and an "emergency response" to mitigate the effects of severe incidents on the system [13].

The *preventive response* is adapted towards strategic grid topology switching distributed energy reserves to control the effects of disruptive events. Predictive tools, especially for weather, are invaluable. Leveraging the use of predictive meteorological equipment can significantly improve forecast accuracy, a critical factor especially for renewable energy sources such as wind and solar power [14].

Implementing these preventive measures becomes more intricate when dealing with unique events like cyber-attacks, earthquakes, and tsunamis, etc.

Phase II: During Disturbance: Detection and Emergency Response is when faced with an extreme event, emergency responses often consider two phases of system outages: the initial impact and subsequent cascading stage.

Initial Outage Phase where components often experience failure or outages due to significant events, typically concentrated in large quantities and specific areas [15]. The processes behind these immediate outages are mainly specific to individual components and use models to forecast potential breakdowns [16]. For instance, during severe weather, there is an increased risk of outages. Earthquakes and strong winds or ice utilize component vulnerability graphs detailing the likelihood of component damage based on the stressor intensity. Large-scale stressors like earthquakes, hurricanes, and floods have complex models that can be integrated with component failure predictions.

Cascading Outage Phase, also "During Event" when this refers to the domino effect where initial outages trigger further disruptions, expanding their reach beyond the initially affected areas. This might also include outages resulting from dependencies on other systems, like ICT infrastructure [17]. In infrequent but high-risk scenarios, cascading effects can lead to large sections of the network going offline. Transmission networks are more prone to cascading outages than distribution networks. Most of these cascading interruptions are a result of safety equipment activations due to altered operational conditions rather than actual component damages. Once the cascading stage stops, the grid's impacted region is identified.

An essential aspect of resilience in cascading outages is the ability to either prevent or minimize the extent and duration of the cascade. Yet, as systems improve, the timings of the initial outage, cascading, and restoration phases may begin to converge. For instance, new outages could emerge during a cascade, and restoration initiatives could commence even as other outages persist [18].

Phase III: Post-Event Restoration and Recovery [9] characterized by *Near-Term post-emergency – Restoration of Services* when the process of electricity service restoration involves progressively increasing generation and reconnecting parts of the network and its load to the transmission systems. Comparable procedures are executed in distribution systems. This involves reviving isolated regions that are not yet reconnected to the primary power system using emergency or black-start-capable generators. Additionally, the grid configuration might be deficient for regular operations due to reasons such as deviation from standard procedures or increased system losses.

Restoration often emphasizes black-start units and seeks feasible line-switching routes compliant with network regulations. As line switching introduces significant dynamic disturbances, addressing stability concerns is crucial.

Longer-Term post-emergency considering that even after service is reinstated for all users, the grid may still be in a compromised state. Desired attributes like N-1 security, efficiency in loss management, and generation distribution in line with operational standards might not be restored. This phase comprises repairing or replacing damaged apparatus and transitioning from emergency states back to market norms. Depending on the damage extent, dependencies on other systems like ICT and transportation, and regulatory context, the sequence of recovery stages may vary:

- Rectifying damaged equipments such as lines and transformers.
- Synchronizing remaining grid segments to restore interconnected operation.
- Replacing backup and emergency setups with regular operational systems.

4. The Cause of Grid Failure

A significant portion of Romania's power lines were designed and built 40 to 50 years ago, using standards that were considered adequate at the time. These lines were designed to withstand climate loads like wind and ice based on data from the 1950s, like Soviet Union regulations. Many of these older lines have lower capacities for wind and ice and have exceeded their 40-year lifespan. Specifically, from 1960 to 1975, 1956 km of 400 kV lines and 2456 km of 220 kV lines were constructed, with an additional 1764 km of 400 kV lines and 479 km of 220 kV lines added by 1985 [19]. These lines now make up about 80% of the network and are showing signs of aging [20].

Starting in the 1970s, updated meteorological data from the Romanian National Institute of Meteorology led to revised standards, improving the accuracy of wind and ice parameters. Since 1985, more and more projects have focused on using current meteorological data and considered the recorded extreme weather conditions over time. Today, current regulations are based on data from the National Meteorological Administration (ANM-2015), which use a 50-year period of return for wind speed and pressure maps, aligning with European design standards (EN 50341-1:2012) [21].

This brief history highlights Romania's transition to a new era of designing stronger and more resilient transmission lines. Now, old lines must meet strict reliability standards, including updated meteorological design criteria for a 50-year return period for maximum wind and specific requirements for transmission lines. To meet current energy demands, withstand extreme weather, and ensure safety, existing transmission lines need detailed studies and necessary upgrades.

The causes of grid failure can be broadly categorized into natural events, human-induced disruptions, operational errors, and aging equipment [22].

Natural causes, including earthquakes, hurricanes, tornadoes (see Fig. 1) floods (see Fig. 2), and ice storms, present considerable threats to the stability of the power grid's physical infrastructure. Earthquakes, particularly in seismically active regions, have the potential to damage transmission towers, substations, and distribution poles. Hurricanes and tropical storms can cause significant damage to power infrastructure, caused by their strong winds, storm surges, and flooding, especially in coastal regions. Ice storms with excessive ice buildup on power lines and towers frequently lead to widespread outages (see Fig. 3).


Fig. 1 Failure caused by tornado combine with strong wind gusts affecting the 400 kV Iernut-Gădălin power line and the 220 kV Iernut-Baia Mare 3 power line in June 2016

Fig. 2 Failure by flooding of tower B224 on 220kV Brazi-Fundeni line, 2008 **[23]**

Fig. 3 Failure due to an ice storm on the 220kV Stejaru-Gheorgheni, 2016

Human-Caused Disruptions significantly threaten grid resilience, including physical damage to infrastructure like transmission towers (see Fig. 4 and 6), substations, and power lines due to accidents, vandalism, or sabotage. This type of damage is usually easy to see and needs fixing or replacing. Additionally, cyber-attacks can target control systems, taking advantage of weaknesses to stop operations and cause long power outages without any physical damage.

Operational Errors, including mistakes made during grid management, can exacerbate failures, particularly during times of high demand or stress. Small initial issues, such as tree contact with power lines, can cascade into larger outages when compounded by human or system errors.

Fig. 4 Failure caused by damage of the transmission tower B174 on the 400kV Rahman-Dobruja line, 2021

Fig. 5 Failure caused by damage of the tower B81 on the 400kV Constanta Nord - Tariverde line, 2022

Aging transmission lines and transformers pose a major concern, as many key components operate beyond their lifespan, making them less reliable. For instance, degraded insulation on transmission lines can cause short circuits, and structural components like the anchors of guided towers (see Fig. 6 and 8) may weaken over time.

Fig. 6 Failure due to the aging anchoring system of transmission guided tower B189 on the 400kV Tariverde - Tulcea Vest line, 2023

Fig. 7 The underground view of tower B189 anchor connection shows reduced anchor cross-sections, leading to failure during extreme weather and ultimately causing the tower to collapse

Older transformers are also more likely to overheating and mechanical failures.

5. Strategy to Anticipate, Prepare, Minimize and Mitigate Disruptions

Many of Romania's power lines, built between 1952 and 1985, were designed with outdated standards. While most of these lines are proposed for replacement or modernization, they generally remain structurally strong. However, some older lines and components are at high risk from extreme weather due to aging and outdated design parameters.

Surveys of overhead power line failures have shown that most structural collapses are caused by strong wind gusts and local tornadoes (e.g., the 400 kV Iernut-Gădălin line). The main issue is that lines built before 1985 were not designed to withstand winds impacting the towers from an angle.

Maximum forces on tower elements usually occur not when the wind hits directly or from the side, but at a diagonal angle, depending on the resistance opposed by each tower face. The critical wind direction for a specific element largely depends on its position on the tower.

In recent years, there have been incidents where aging power line components failed, leading to the collapse of metal towers under severe winter weather conditions (e.g., B189 of the 400 kV Tariverde - Tulcea line). In these cases, the aging components were at a higher risk of failure. The combination of aged line elements and strong winds caused the already weakened anchors of the B189 tower to be pulled out of their foundation, resulting in the tower's collapse.

These events can create additional loads that exceed the design capacity of the transmission networks. Moreover, the failure of a single power line structure often leads to the collapse of a larger section of the network through cascading failures in the affected area.

For example [21], a study on a random SnY 400104 suspension tower used on the 400 kV CNE Cernavodă – Gura Ialomiței II transmission line in the Dobrogea region, initially designed in the 1970s, revealed it was meant to handle transverse loads of approximately 2548 daN under normal conditions (N1), according to the design standards of that time. Under N1 conditions, this means maximum wind acting at a 90-degree angle to the power line.

Due to increased maximum wind speeds in the Dobrogea area, where the line is located, the transverse load value, according to the new SR EN 50341-2:2024 design standard based on meteorological data from the National Meteorological Administration (ANM – 2015), has risen to about 3957 daN, a 55% increase compared to the initial design conditions.

For N2 conditions, which involve maximum wind combined with ice deposits acting at a 90-degree angle to the power line, the transverse loads increase from 3454 daN under the initial design standard to 5620 daN under the current standard. This represents a 62% increase according to the new design standard compared to the original design.

Due to increased loads and aging infrastructure, transmission operators are seeking solutions to ensure continuous service. It is essential to have a proper evaluation and maintenance program, as failures can occur in the weakest components that no longer meet current standards or are significantly aged.

When considering ***planning and design*** in the electric utility sector, it's essential to move beyond just economic efficiency. Historically, utility planning has been focused on optimizing for normal operations and ensuring system reliability under known conditions. However, designing for resilience requires addressing the system's ability to withstand unexpected and catastrophic events, which calls for a more holistic approach. This includes considering the resilience of both individual components and the system, accounting for interdependencies with infrastructures like natural gas and communication systems. Investments should aim not only at reliability but also at enhancing adaptability, redundancy, and long-term sustainability [24].

Certainly, structures can be designed to handle new weather challenges, but the key is to make them "smarter" rather than just "stronger." This approach ensures energy systems are safer, more adaptable, and can quickly recover from failures. Instead of focusing on "losing structural security," which emphasizes robustness, we should focus on "security during structural loss," which emphasizes absorbing impacts and quickly restoring services.

Sources like the Lawrence Berkeley National Laboratory emphasize that resilience-focused planning must go beyond traditional metrics, integrating considerations for extreme weather and grid constraints. This shift ensures that the grid is robust against future uncertainties, including environmental and technological shifts [25].

The inspection of existing power lines and the design of new ones should be based on the latest information provided by meteorological monitoring agencies, which should include updated statistics and territorial maps with specific meteorological parameters. For the studied areas where weather conditions exceed the initial design limits of overhead power lines, such as wind speed or ice weight, their structural elements, including metal poles, should be inspected to ensure resistance to more severe weather conditions, such as stronger winds, thicker ice layers, and combinations of wind and ice.

Reinforcement of poles and towers is another key factor to improving the resilience of the transmission and distribution (T&D) network, especially in regions vulnerable to heavy winds or ice accumulation. This structural reinforcement, which enhances the robustness of the network, involves a cost-benefit trade-off but offers significant benefits in preventing damage during extreme events.

Transmission line support towers rely on adjacent towers and conductors for stability. The conductors on both sides are tensioned, with forces equally distributed to maintain balance. If these forces disappear on one side, the tower becomes unbalanced and may fail.

When this configuration becomes unbalanced and a metal tower collapse, it can trigger a domino effect, causing adjacent towers to fail one after another in a cascading manner. To reduce the risk of cascading failures, utility companies install additional tension towers, which provide extra support and help prevent the spread of failures. However, there is a trade-off between installation costs and the desired level of safety, depending on how frequently these structures are installed.

Maintenance tasks help identify equipment close to its operational lifespan or likely to fail, necessitating their replacement.

Distributed energy resources (DERs), including photovoltaic systems, diesel generators, small natural gas turbines, battery storage, demand response, and ***microgrids (MGs)***, are vital for preventing large-scale outages and supplying power to critical services during emergencies. They also support the rapid restoration of key load points on distribution networks [26].

Reinforcing vulnerable components is essential to ensure power delivery to critical loads during extreme conditions. The importance of ***smart grid solutions*** in enhancing power system resilience is increasing, particularly at the distribution level. This infrastructure includes ***Advanced Metering Infrastructure (AMI)***, remote control systems, telecommunications, data management, and Distribution Management Systems (DMS)/Energy Management Systems (EMS). Combined with a ***SCADA/DMS configuration***, these tools enable real-time monitoring, remote operations, and improve control and management of distribution networks down to MV/LV substations.

Smart grid applications, such as fault location, isolation, and service restoration (FLISR) offer real-time analytical capabilities and enhance decision-making for distribution networks. However, one of the drawbacks of a heavy dependence on smart grid technologies is the heightened reliance on communication systems, which might face disruptions post resilience events [27].

There is significant potential to enhance both physical and cyber resilience in real-time electric grid operations. Integrating smart grid devices increases the grid's intelligence through advanced sensing and automation, such as ***real-time monitoring system***s that collect data from sensors across transmission and distribution networks. These systems send control signals and include technologies to monitor the health of circuits and components. Combined with SCADA systems or computer models, this approach improves control and monitoring of the power grid in operation or during an extreme weather event.

Developing computer models to simulate transmission line demands during extreme weather events is crucial for preparing to limit damage and restore the power system's functionality. These models help accurately assess the impact of severe weather on transmission lines, predict potential failures, and plan effective responses. Techniques like Sequential Monte Carlo simulations capture the unpredictable nature of weather and evaluate various measures to enhance grid resilience. This approach improves risk management, emergency preparedness, and recovery speed, ensuring that the power system remains strong and can quickly return to normal operation after disruptions [28].

Despite technological advancements, human operators remain essential, highlighting the need for better tools to enhance system management [29]. The grid typically operates under the N-1 reliability criterion, ensuring stability even when a single component fails. Operators are well-trained to manage both normal and critical situations, such as alerts and emergencies. However, ongoing improvements are necessary to further strengthen resilience during challenging events.

6. Conclusions

To prevent incidents and reduce the impact of failures on overhead power lines and their components, the following measures have been implemented in Romania:

- Climate zoning of the territory using detailed data on maximum wind speed and ice thickness (according to ANM – 2015).
- Application of the latest design standard SR EN 50341-2-24 for power lines with voltages above 1 kV, based on the EN 50341-1:2013.
- Establishing load criteria to prevent the effects of weather-related failures and cascading failures.
- Analyzing the effects of aging on the performance of overhead power lines.
- Adopting modern design methods for structural elements of power lines.
- Developing a universal rapid-deploy emergency tower for replacing collapsed transmission towers in case of failure.

Future research is needed to quantify the interdependencies between critical infrastructures and enhance the resilience of energy systems. The literature review highlights several key aspects for improving energy system resilience, including:

- Assessing the cost-benefit ratio of resilience strategies.
- Promoting collaboration among energy operators.
- Strengthening resilience by integrating renewables.
- Identifying system vulnerabilities through data analysis.
- Evaluating vulnerabilities to cyber threats.
- Identifying major High-Impact Low-Probability (HILP)
- Developing advanced resilience indicators and analytical tools to cover various scenarios.
- Introducing artificial intelligence and machine learning in resilience modeling and quantification.

Although these systems are reliable under normal operating conditions, they can fail in the face of extreme events. For an electrical infrastructure to be both reliable and resilient, a deep understanding of resilience as a dynamic and evolving concept is necessary. Unlike reliability, which is well-defined, resilience remains vague, especially in terms of modeling and quantifiable assessments. A truly resilient system must not only be robust and adaptable but also capable of learning from past events and anticipating future ones.

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