Centralized vs. Decentralized Electric Grid Resilience

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Escalating events such as extreme weather conditions, geopolitical incidents, acts of war, cyberattacks, and the intermittence of renewable energy resources pose substantial challenges to the functionality of global electric grids. Consequently, research on enhancing the resilience of electric grids has become increasingly crucial. Concurrently, the decentralization of electric grids, driven by a heightened integration of distributed energy resources (DERs) and the imperative for decarbonization, has brought about significant transformations in grid topologies.

Keywords: electric grid ; resilience ; centralized ; decentralized

1. Introduction

Modern electric power supply systems are governed by three key criteria: quantity, quality, and reliability. Quantity involves maintaining a balance between power generation and demand, while quality ensures that supplied electricity aligns with predefined characteristics such as voltage and frequency. Reliability, a crucial aspect, is defined as the consistent delivery of electricity without interruption or significant fluctuations, requiring stable flow, demand-meeting power generation, and minimal disruptions from various factors. Grid resilience is a fundamental element in ensuring the reliability of electric grids. It is characterized by the grid's ability to endure and recover from various disruptions or unforeseen events, such as natural disasters, cyberattacks, or equipment failures [1]. This resilience encompasses the grid's capacity to absorb shocks, adapt to dynamic conditions, and swiftly restore power following an outage. Strategies to enhance grid resilience often involve leveraging diverse energy sources, establishing a robust infrastructure, and implementing rapid response mechanisms. In contrast, reliability primarily aims to prevent disruptions and maintain an uninterrupted power supply.

Grid resilience has become paramount in the contemporary energy landscape due to heightened reliance on electricity across all economic sectors. The interdependency of critical infrastructures, particularly electricity, communications, healthcare, and transportation [2], further underscores the significance of prioritizing grid resilience. Additionally, national security and independence concerns accentuate the urgency of ensuring grid resilience. Consequently, policymakers, utility companies, and governments worldwide have prioritized fortifying the resilience of electric grids [3].

Electric grids originated in the late 19th century as small-scale, primitive, and isolated town-based networks (Grid 1.0). However, driven by a growing reliance on electric power and a substantial surge in energy demand, electric grids evolved into national, large-scale centralized power grids centered around significant power plants (Grid 2.0). A new transformation occurred in less than a century, spurred by the imperative to decarbonize the energy sector. This shift, driven by the increasing integration of renewable energy (RE) systems and DERs, led to a decentralized topology (Grid 3.0).

Today, with the advent of advanced technologies such as artificial intelligence (AI), the blockchain, the Internet of Things (IoT), and the incorporation of concepts like peer-to-peer (P2P) energy trading, energy democracy, and virtual power plants (VPP), the grid is progressing towards complete decentralization, shaping the vision of the future grid (Grid 4.0) as a composite of thousands or even millions of microgrids. Simultaneously, these transformations in the electric grid's topology align with a surge in digitalization. Recognizing the necessity to address evolving needs and challenges, a core digital transformation occurred at the grid's operational and asset management levels. The integration of smart metering, advanced metering infrastructure (AMI), and the application of digital technologies for automation and optimization underlined the digital revolution in the electric grid [4]. Undoubtedly, the evolution of the electric grid into a decentralized, highly digitized network significantly enhanced its operational flexibility. **Figure 1** depicts the progression of the grid's topology, digitalization, and flexibility.

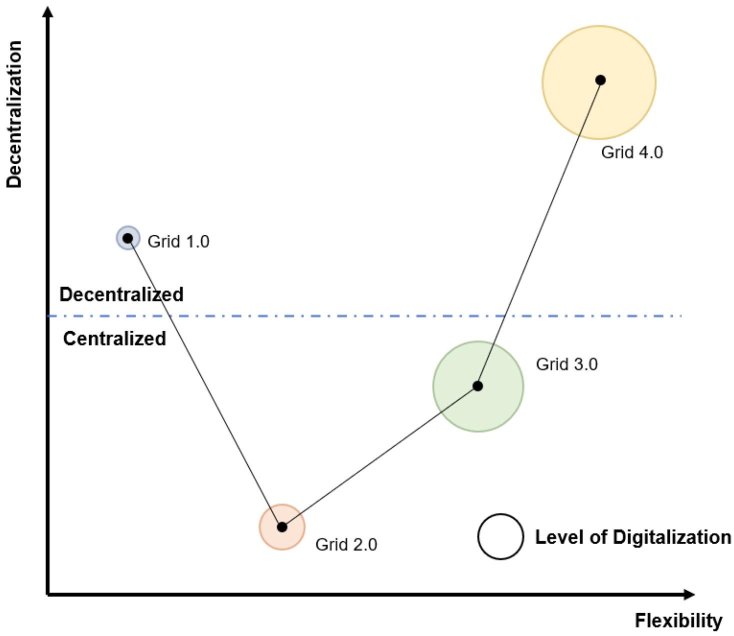

Figure 1. The electric grid's changes with time.

However, within the domain of grid resilience, ongoing discourse and analysis revolve around the advantages and disadvantages of centralized and decentralized approaches. Centralized approaches to grid resilience adopt a centralized control architecture, where decisions and actions are coordinated and executed by a central authority or operator. This approach provides superior controllability and predictability, facilitating efficient resource management and response to disruptions. Nonetheless, centralized networks have a notable drawback, known as a single point of failure (SPOF). This refers to a specific grid element, such as a control center, power station, or transmission line, whose failure can significantly disrupt or potentially collapse the entire grid's functionality. Essentially, it represents a vulnerability that, if compromised, could result in widespread power outages or disruptions [5].

Conversely, decentralized approaches to grid resilience embrace near-edge solutions, including small-scale power generation and energy storage systems [6]. This decentralized architecture provides a heightened level of scalability, allowing for greater flexibility. Additionally, decentralized systems have demonstrated increased resilience in the face of climate-related risks such as wildfires and extreme storm events. Distributed energy systems can effectively mitigate damage or disruption to primary utility components by leveraging end-user solutions like small generators, rooftop solar photovoltaic (PV) systems, and battery energy storage systems (BESS), enhancing overall resilience.

2. Centralized vs. Decentralized Electric Grid Resilience

Electric grid operators globally face a persistent challenge posed by natural, non-natural, predictable, and unpredictable factors. These elements can compromise the flexibility and reliability of the grid [7]. Incidents like extreme weather conditions, geodesic events, wildfires, acts of war, and cyberattacks constitute genuine threats to the electric grid's reliability. Consequently, there has been an increasing interest in recent research on electric grid resilience. However, a notable majority of these studies in the energy sector concentrate on centralized grids.

The initial phase in comprehending the issue of electric grid resilience involves defining it and establishing a framework. Article [8] delves into various terminologies related to grid resilience, presenting a comprehensive framework that defines the concept and explores diverse quantitative metrics and approaches for evaluating grid resilience. In [9], Liu et al. formulate a resilience assessment framework to design more resilient transmission lines, especially in the face of extreme weather events. Meanwhile, Jasiunas et al. [10] reviewed energy grid resilience and proposed a framework for mapping potential threats. To understand threats and vulnerabilities that compromise electric grid resilience, Sakshi et al. [11] define microgrid resilience, conducting an in-depth analysis of threats, vulnerabilities, and mitigation techniques. Furthermore, Nguyen et al. [12] surveyed the vulnerabilities of modern electric grids to cyber-attacks.

Addressing resilience strategies, ref. [13] introduces a multi-stage stochastic robust optimization model to enhance the management of distribution network resilience. The works presented in [14][15] comprehensively review recently adopted strategies to bolster grid resilience. In grid resilience, a central challenge lies in determining how to measure resilience and identifying the relevant metrics. In [16], Das et al. provide an in-depth exploration of the metrics for a resilient grid and the challenges and limitations involved in formulating and calculating these metrics. The study in [17] also delves into metrics that enable quantifying energy grid resilience, offering insights into proposed enhancement techniques.

Recent research also delves into electric grid resilience's regulatory and socio-economic dimensions, recognizing their pivotal roles. Regulations are instrumental in ensuring and enhancing grid resilience, providing a framework for utilities, operators, and stakeholders to manage, maintain, and upgrade grid infrastructure to withstand diverse challenges and disruptions. Article [18] examines federal regulations related to a resilient electric grid in the United States of America. From a complementary perspective, the active involvement of prosumers in energy production, consumption, and management diversifies grid resources, enhances flexibility, and contributes to overall improvements in electric grid resilience. The significance of the active role of prosumers in operating a modern electric grid is highlighted in the study presented in [19].

The currently applied metrics for grid resilience measurement are indices such as the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI), which measure the frequency and duration of outages experienced by customers over a specific period. Nevertheless, these metrics can only be calculated once incidents have occurred. Another method to simulate the grid's resilience is to use computer simulation techniques such as dynamic system simulation models. These models simulate the transient behavior of the grid, including the response to sudden changes such as equipment failures, disturbances, or switching events. This technique helps to assess the grid's stability, reliability, and response under various dynamic conditions. However, dynamic system simulation models can be highly complex, requiring detailed data on grid topology, equipment characteristics, control systems, and operating conditions. They may require significant computational resources, high-performance computing infrastructure, and long computation times, especially for large-scale grids with numerous components and complex interactions. Another used technique is Monte Carlo simulation. This technique involves running multiple simulations with randomly generated input parameters to assess the probabilistic behavior of the grid. It helps to evaluate the likelihood and impact of different events, such as extreme weather events, equipment failures, or cyberattacks, on grid resilience. Yet, Monte Carlo simulation involves running many iterations to simulate the probabilistic behavior of the grid under different scenarios. This also requires significant computational resources and time, especially for complex grid models or when simulating rare or extreme events. Also, this simulation relies on accurate and representative input data, including probability distributions for different parameters such as weather conditions, equipment failures, and demand patterns. Obtaining and validating these data can be challenging, and data uncertainties or inaccuracies can affect simulation results. Running Monte Carlo simulation also requires computational resources and expertise in statistical analysis, simulation techniques, and grid modeling. Small utilities or organizations with limited resources may struggle to implement Monte Carlo simulation effectively without access to specialized software, personnel, or external support. Therefore, the methodology for simulating the grid's resilience uses a simple mathematical model that does not require significant computational resources, unique expertise, or minimal simulation time.

On the other side of the spectrum, grid interruptions, such as power outages, can have profound and multifaceted impacts on the economy, affecting consumers and various sectors. This impact is elucidated in [20], where a dynamic inoperability input–output model (DIIM), combined with a customer interruption cost (CIC) model, is employed to assess the economic consequences of power interruptions. Likewise, the IIM has found applications in various economic analyses related to unexpected events and perturbations. In [21], Xu et al. introduced a dynamic IIM to simulate economic sector dynamics during emergencies, specifically when facing value-added perturbations or interruptions. Another instance is found in [22], where Jin et al. utilized the IIM to analyze the economic impact of COVID-19 in Shanghai. However, the utility of the inoperability input–output model extends beyond economic analysis. Numerous researchers have employed Leontief's input–output model to model and analyze the resilience of infrastructures and networks. For instance, in [23], Jia et al. applied the IIM to analyze the effects of disturbances, such as droughts, earthquakes, and terrorist attacks, on water systems in industrial parks.

Similarly, ref. [24] employed the IIM to analyze cascading effects induced by critical infrastructure dependencies. Nevertheless, much of the research on electric grid resilience primarily focuses on the traditional centralized electric grid as a fundamental model. While many articles underscore the significance of DERs in enhancing grid resilience, a detailed exploration of measuring this resilience with associated metrics is often lacking. Drawing from definitions, frameworks, and measurement metrics established for electric grid resilience and inspired by the application of the inoperability Input–output (IIO) model in similar contexts, this research proposes a comparative analysis between centralized and decentralized electric grids in terms of resilience. The objective is to quantify the importance of DERs in improving grid resilience and mitigating its vulnerability to unexpected perturbations and interruptions.

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