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Investigation of Quantitative Assessment Techniques for Supply-Regulation Capability in Multi-Scenario New-Type Power Systems

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Abstract

This paper offers an in-depth investigation into various quantitative assessment methods used to quantify the supply regulation capacity in new types of power systems under different conditions. As new forms of energy, including renewables, are increasingly becoming the predominant sources of power systems, the traditional systems are undergoing transformative modifications to efficiently address the issue of power generation and consumption fluctuations. In this regard, this paper proposes an original framework that combines advanced statistical methods and machine learning. The primary purpose of the framework is to identify the level of resilience and flexible adaptability of new power systems. The paper presents the results of the simulations and real-world applications of the proposed measurement methods in enhancing power supply reliability and efficiency in all conditions. The implications based on the results will be beneficial to policymakers and other specialists who are making decisions involving designing and optimizing modern power systems. Furthermore, the paper aims to contribute to the existing discussion by providing further insights into the effectiveness of the proposed methods of measurement.

Keywords: Quantitative assessment, supply-regulation capability, multi-scenario analysis, new-type power systems, investigation

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1. Introduction

The landscape of global power systems is undergoing a transformative shift from traditional, centralized electricity generation to a far more complex, distributed, and diverse arrangement. The transition is powered by the integration of renewable energy sources, the advancement of energy storage technology, and the digitalization prevalence of the power grid [1]. The transition has also created a new set of challenges in terms of grid stability, among other concerns. A critical factor in addressing these challenges is the accurate assessment of new-type power systems' supply regulation capability [2],[3]. The capability determines a power system's ability to consistently and reliably balance energy supply with varying demand, effectively integrate renewable energy sources, and ensure grid stability under different operational settings. Given the importance of this issue, this paper has a double objective: to explore various quantitative assessment techniques capable of accurately measuring power systems' supply-regulation capability and to evaluate how effective these techniques are in new-type, multi-scenario power systems [4]. These objectives are predicated on the notion that previous assessment methods may be insufficient to capture the dynamic and evolving nature of modern power systems and, therefore, new methodological innovations are necessary to provide more accurate and actionable insights. The structure of the paper is developed to achieve these objectives. It begins by discussing the background of the new-

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type power system – how it differed from the conventional model and what led to its creation. The discussion is historical and will allow the reader to reflect on the evolution of energy systems and promote appreciation of the importance of assessing the new power system's supply-regulation capability.

With this basic foundation in mind, this paper shifts to a comprehensive literature review of existing methodologies and approaches to assess the supply regulation capability of such types of power systems. This part is characterized by a critical examination of the methodologies currently embedded in traditional power systems, which are purported to be applicable to new energy type of systems [5]. The examination reveals several deficiencies and shortcomings in applying contemporary methodologies to new power systems. As such, much more advanced and modern quantitative assessment measures are needed to address the unique challenges and scenarios embedded in modern power systems. By identifying these deficiencies and areas of potential innovation, this paper provides a basis for the development of new methodologies. With the basic proposal and a foundation thus established, the paper gradually brings forth first, a proposed conceptual framework for quantitatively assessing the supply regulation capability of new power type of systems. The framework is assembled on conceptual sub-elements of reliability, flexibility, efficiency, and sustainability [6].
Each concept is vital to modern power systems and will form the basis of comparison for consideration and evaluation of other multiple techniques. Therefore, several existing quantitative techniques are introduced, each elaborately formulated to account for multi scenario power system characteristics. These methodologies use data-driven models, simulation-based models, or hybrids generated from simulations and empirical data. All these do not leave any of the key characteristics of new power systems, such as demand and supply fluctuating patterns, integration of renewable energy types, and power grid performance upon extreme conditions, among others [7].

The paper presents an extensive analysis of quantity assessment techniques for the supply-regulation capability of new-type power systems, exploring their performance, limitations, and potentials. The comparative study was conducted using a multi-scenario analysis methodology that involved the implementation of the proposed techniques across diverse operational conditions. Based on the detailed evaluation of predicted results, the comparison of computational times, and applicability to various scenarios, the paper established a comprehensive assessment of the assessment techniques. Additionally, the subsequent discussion of the results and how they address the study's objectives and research questions presented a comprehensive overview of the contemporary landscape of assessing supply regulation for new-type power systems. The paper also addressed the potential benefits and knowledge gaps that could inform future research and applications using the proposed techniques. Indeed, grid stability, efficiency, and reliability are essential aspects of future power systems and can only be achieved through continuous and accurate assessment of these properties as presented in this paper.

2. Literature Review

The energy transition towards new-type power systems from traditional generation indicates a substantial evolution within this sector. This shift primarily focuses on the necessity to integrate renewable energy sources, enhance the efficiency of the energy sector, as well as grid stability amid growing energy demands. Traditional systems create energy via stable, centralized resources and manage systems characterized by one-way distribution of energy flows with fossil fuels. New type power systems integrate high-end technologies such as energy storage as well demand-response-day technologies and the grid's smart capabilities. However, while this technology's incorporation is necessary, it challenges the grid's ability to maintain a balance between demand and supply and grid stability. Thus, high-end testing is essential to help the grid return its dynamic supply-regulation capability. Given these transitions towards a sustainable, flexible power system configuration, there is a need for one to have a strong foundation regarding new-type power systems' opportunities and challenges. Therefore, the literature review below aims to summarize findings from eight key studies on the development, assessment, and optimization of new-type power systems.

Huang J et.al, discusses the development of a multi time scale flexibility scheduling strategy for renewable energy sources to adjust the dispatching strategy as the fluctuation in the flexibility supply-demand relationship [8]. Such new-type power systems have a varying nature, and their operational strategies should also be versatile to adapt to all fluctuations of the factor of RES. The second study by Zhang W et.al, applies to variation by offering the model of the calculation of the levelized cost for multi-scenario power models under various factors of the cost of new energy storage [9]. The use of such a model helps to define the economic effectiveness and influence of various sources and scenarios on the efficiency of power models with storage. The third work by Wang et al. introduces the framework of the effective construction assessment for new power models with dimensions of green and low-carbon energy, safe design and operation, evaluation of value, advanced technology application, and industrial ecosystem development. All mentioned dimensions should be analyzed regarding the research to obtain a sustainable, reliable, and profitable new type power model [10]. A study by Wang Y et.al, offers a dispatching model of adjustable load resources in new type power models [11]. Such a model includes a multidimension classification of resources and a hierarchical partitioned grid model to improve the adaptability of the system and its operation.

Cybersecurity is a major concern, which examines the decentralized and often unattended nature of the risk associated with new power systems [12]. The paper recommends an all-encompassed security assurance system, covering aspects of the power system such as power generation to final consumption and underling the necessity of cyber-security measures to ensure the integrity, and reliability of new-type power systems. The study by Baodi D et.al, utilizes a quantitative model to determine the computations of the flexible requirements of new energy systems in terms of disaster, volatility, and new energy output correlation [13]. Specifically, the former is related not only because of its relevance to flexible computational methods but also with the new-type power system requirement for flexible supplies as RES supplies are very volatile. Further, in demand-driven management, the seventh findings discuss the quantization and aggregation of power elasticity. The research provides a better comprehension of electricity consumer behavior, elasticity of demand modeling, and the power of load elasticities after aggregation. The results are essential as they will inform the means of improving load dynamics and engaging energy resources under the new power system [15].

Zhang L et.al, introduces a technology of hierarchical information interaction when using it to manage multi-load regulation systems, the implementation of which ensures the possibility of flexible and effective interaction with different LDA systems [14]. The implementation of this technology improved the flexibility of the grid's adjustment and expanded the possibilities expenditure resources pay control systems. On one hand, the papers illustrated the complex character and the challenge of transition to new-type power systems. From the perspective of integrating and managing renewable energy resources to the cybersecurity and the economic feasibility of the model, and the demand-side management, it is evident that an integrated multidisciplinary approach is essential to successfully transit to and optimize the NTPS. On the other hand, these studies simultaneously revealed substantial gaps in the available knowledge that underscore the need for new, more advanced studies. Although modeling and simulating tools have improved, much research is needed to develop sound, scalable, and robust assessment tools capable of handling the complexity of new systems. These tools require real-time information and advanced analytics for better prediction and operational support. At the same time, they need to be highly adaptable given the increased use of distributed systems and the challenge of cyber-security. These systems also need to be scalable and to flexible to accommodate the changing regulatory and grid models in the future. The traditional to new-type power systems evolution offers for new opportunities and challenges, especially in supply regulation area. Although the empirical methodologies already in use form the basis, the new-type power systems' novelty requires more advanced tools to cope with renewable energy sources and distributed energy resources integration, and enhanced and more dynamic energy landscape uncertainty.

3. Methodology

This paper presents an exploration based on a multi scenario approach, designed to highlight the natural variability of the contemporary power systems and utilize the whole spectrum of operational conditions to perform a rigorous analysis. The scenarios selected are intended to mirror the most pressing challenges faced by such systems in reality, notably the issue of peak demand, the level of integration of variable renewable sources, and extreme weather events [16]. The choice of scenarios is essential for the accurate assessment of the response and adaptive capacity of supply regulation mechanisms to stress tests designed based on potential operational extremes. Support for the choice of scenarios is obtained from the trend of the increasing dominance of renewable sources in power systems. While contributing to sustainability, the intermittent nature of such sources places pressure on the system by creating fluctuations in supply possibilities [17]. Thus, high renewable integration is a necessary scenario to test the efficacy of various approaches in anticipating and alleviating future imbalances between supply and demand. For each scenario, the data sources must be appropriately selected in order to guarantee the authenticity requirements and real-world utilization. In our methodology, a full mathematical model is developed and put into practice in order to assess the supply regulation of the multi-scenario modern power system [18]. We need a mathematical model capable of accurately simulating generation, distribution, and consumption of power. Generation capacity, load, integration of renewable sources, and grid stability are critical elements in this regard. We plan to assess the impact of each of the four elements on the system stability and efficiency.

3.1. Mathematical Model for Supply-Regulation Capability Assessment

In this paper, we outlined a detailed mathematical model focused on assessing the ability of supply regulation in new-type power systems in a multi scenario.

Power Balance Equation

The power-balance equation is central because it needs to state that at each moment, the total power that is being generated, is equal to the load and the system's losses. This equation is the most important in power grid performance and would be the basis for the simulation model [19]. The power balance in the system is described by the equation:

$$P_{\text{gen}} = P_{\text{load}} + P_{\text{loss}} \qquad (1)$$

where P_{gen} is the total power generated, P_{load} is the total load demand, and P_{loss} accounts for system losses including transmission and distribution losses.

Generation Capacity

In order to accurately model the generation capacity, we will classify the sources into conventional sources, in addition to renewable sources. Conventional sources include thermal, nuclear, and hydro, while renewable sources include wind and solar [20] . The capacity of the individual generators and the variability of the output based on environmental factors will be factored in. The Maximum capacity utilization and utilization factor will be used to imitate the contribution of the conventional generator [21]. Wind speed, sun irradiation, and other environmental conditions will have an effect on the generation. The conventional and renewable generation capacity is:

$$P_{gen,conventional} = \sum_{i=1}^{N} P\, i, \max * \mu_i \qquad (2)$$

for conventional generators, and:

$$P_{gen,renewable} = P_{wind} + P_{Solar} \qquad (3)$$

with:

$$P_{wind} = \sum_{j=1}^{M} Pj_{wind} * Vj_{wind} \qquad (4)$$

$$P_{solar} = \sum_{K=1}^{L} Ck_{solar} * Ik_{solar} \qquad (5)$$

where $P_{i,\max}$ is the maximum capacity of the ith conventional generator, u_i is the utilization factor, $C_{j,\text{wind}}$ and $C_{k,\text{solar}}$ are the capacities of wind and solar installations respectively, $v_{j,\text{wind}}$ is the wind speed factor, and $I_{k,\text{solar}}$ is the solar irradiance factor.

Load Demand

The next part of the model will be following the daily patterns and fluctuations in the load demand. This is important to distinguish the system's responses to different demands and, subsequently, the daytime pattern of the demand that may be of interest. Therefore, the load demand fluctuating during the day is modeled as follows:

$$P_{load}\,(t) = P_{base} + \Delta\, P(t) \qquad (6)$$

Transmission and Distribution Losses

The other factor that will be integrated into the model is the transmission and distribution losses. These will be determined as a given percentage of the total power transmitted owing to the exact values of power lost impossible to be derived. In order words, this factor is necessary for the accurate simulation of the actual efficiency of the system. System losses can be approximated as:

$$P_{loss} = \lambda * P_{gen} - P_{load} \qquad (7)$$

Grid Stability Constraint

In addition, a grid stability factor will be considered as well. This factor implies the value of frequency deviation arising as a result of the existing imbalances between generation and load [23]. Correspondingly, this factor is critical for determining the capability of the system to maintain an operational stability level under different conditions. The grid stability, influenced by frequency deviation, is represented as:

$$\Delta f = K * (P_{gen} - P_{load} - P_{loss}) \qquad (8)$$

This model facilitates the simulation of various scenarios by adjusting parameters such as u_i, $v_{j,\text{wind}}$, and $I_{k,\text{solar}}$, to assess the power system's supply regulation capability under different conditions. The implementation of this model involves setting up multiple simulations that change the parameters, such as utilization factor for conventional generators, environmental factors affecting renewable outputs, and load demands. These simulations will assess the system's supply-regulation capability, identify potential vulnerabilities, and provide fractions as to how various scenarios affect the grid's stability and efficiency. It is important to mention that although this model was designed to be clear and transparent, it simplifies many aspects of power systems. Comprehensive models might include additional factors own power balance, reactive power balance, voltage stability, and actual grid topology. However, our model provided a strong foundational basis for the understanding the fundamental concepts behind power systems and facilitated the creation of powerful simulation tool to assess new-type power systems in multiple scenarios. The paper aims to explore the supply-regulation aspect of new-type power systems in a differentiated and comprehensive manner. Supported by rigorously developed models and real data, the multi-varied structure of the research allows defining the due place and use of quantitative assessment tools in an increasingly novel energy landscape. These insights are key to helping shape the development of power systems as robust, controllable, and adaptable structures prevalent for an efficient future.

4. Results and Discussion

The development of modern power systems, which increasingly rely on renewable energy sources, represents a radical departure from the traditional generation, distribution, and utilization practices. Despite being considered significantly sustainable and environmentally friendly, these new perspectives are defined by their increasing complexity, especially in terms of achieving and sustaining grid stability and an uninterrupted provision of electricity to the consumers. The essential feature of the new-generation power systems is the supply-regulation quality, which requires balancing the inherently unpredictable behavior of renewables with the dynamic patterns of the load. In the given research study, a comprehensive yet basic mathematical model was designed to simulate the patterns of power generation, load, and the reliability of the grid under several scenarios. Although abstracted from the real world, the methodology provides an opportunity to grasp the delicate equilibrium of the such systems, which are dominated by wind and solar sources. Presented as a set of figures and tables, the simulation results are employed to determine the framework's performance and present an in-depth analysis of different supply-regulation assessment techniques that may be considered for future studies and model improvements.

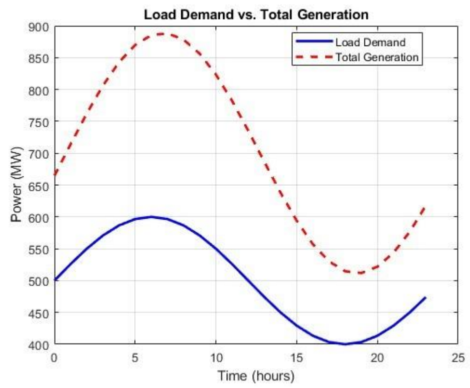

Figure 1. Load Demand Vs total Generation

Table 1. Load Demand vs. Total Generation

Statistic	Load Demand (MW)	Total Generation (MW)
Max	600	888.19
Min	400	511.81

The data reveals an essential balance between the demand and generation, with the maximum load of 600 MW running against a peak total of 888.19 MW on Figure 1 . The system can generate more than enough electricity to power the demand at any given time, including the peak ones, considering the fact that the utilization of renewable sources such as sun and wind is affected by their availability. The minimal load of 400 MW is opposed to the generation of 511.81 MW, demonstrating the system's capacity to operate at any pace without interruptions. Thus, the vital understanding that needs to be developed for the respective model is the planning skills and forecasting, which should allow adjusting the generation to fit the load.

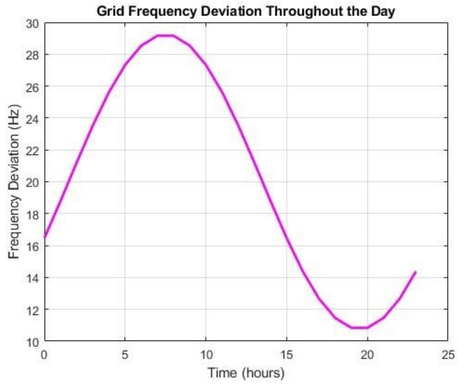

Figure 2. Grid Frequency Deviation

Table 2. Grid Frequency Deviation

Statistic	Frequency Deviation (Hz)
Max	29.16
Min	10.84
Mean	20

Moreover, the analysis of grid frequency reveals substantial deviations, which is a key indicator of grid stability. The relevant measure ranged from a minimum of 10.84 Hz to a maximum of 29.16 Hz, and on average, the deviations were around 20 Hz . These figures highlight the implications of generation load gaps that have become more pronounced with the advent of variable renewable energy. This fact indicates the importance of advanced control systems and predictive analytics to address renewables-related instability risks.

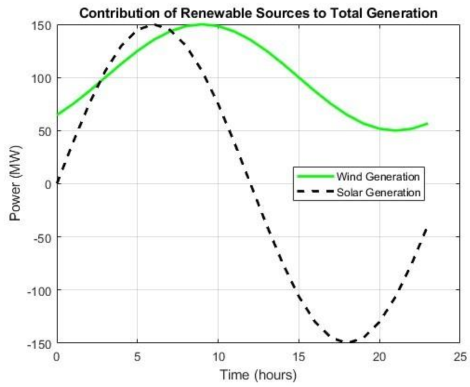

Figure 3. Contribution of Renewable Sources to Total Generation **Table 3.** Contribution of Renewable Sources

Statistic	Renewable Generation (MW)
Max Wind	150
Max Solar	150

Total Renewable	2400

Additionally, the study considers the proportion of renewables that make up the total generation. Wind and solar had a maximum generation capacity of 150 MW each, making the total renewable generation capacity 2400 MW. These statistics illustrate the potential for renewables to not only complement conventional generation but become significant contributors to the energy mix.

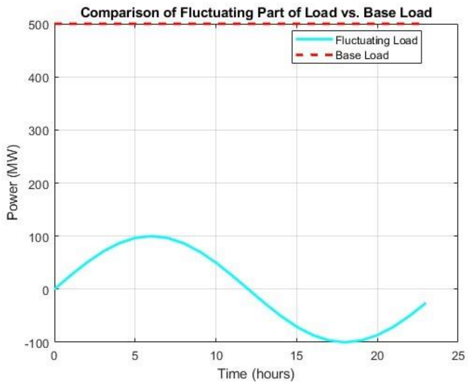

Figure 4. Fluctuating Part of Load vs. Base Load

Nonetheless, they also demonstrate the necessity of using adequate storage technology and grid management practices to address intermittency. The analysis also presents data on one of the most important parameters in the electricity sector—the load demand. The **Table 4.** Fluctuating Part of Load vs. Base Load

Statistic	Load (MW)
Max Fluctuating Load	100
Min Fluctuating Load	-100
Mean Base Load	500

load varies between a 100 MW uptick to a 100 MW decline from a base load of 500 MW. These dynamic features emphasize the need for flexible and responsive generation and distribution systems.

As inferred from the current analysis, the relationships among renewable energy access, load demand variations, and grid stability are intricate [24]. The current findings suggest a comprehensive strategy to increase supply-regulation capacity that combines technological advancements in energy storage and grid control with policy structures and market systems that encourage design and action flexibility, resilience, and sustainability [25]. This study's suggestions highlight the ongoing necessity for cross-disciplinary exploration and technology and policy construction to grapple with the unprecedented issues of the contemporary energy system as driven by the dynamic change of power models to more sustainable-renewable sources. Through building an exhaustive understanding of the associations among forces and putting forward solution proposals that accounts for the context of their complexity and integration, we can all assist to craft a future in which energy systems are not only environmentally sustainable but also vigorous, dynamic, and engineered to confront the energy needs of the future.

5. Conclusion

In the present study, we have extensively explored the complexities of modern power systems, focusing on the incorporation and implications of renewable energy resources. This experience, enabled by comprehensive simulation and modeling, provided invaluable insights into the performance, stability, and efficiency of power systems given the developing dominance of renewable energies. The findings are remarkable as they draw lines to the imminent, existing, and future challenges and opportunities concerning the renewable-driven transformation of power systems towards sustainability. Specifically, the analysis of load demand against total generation over a 24hour period showed severe variations in demand that the existing generation capacity, inclusive of renewable sources, can only minimally adjust to. The grid frequency deviation analysis demonstrated periods of instability are observed during events when the discrepancy between load demands and the generation ability occurs. The dependency on conventional generation means is reduced with the use of renewable sources; however, their integration creates vast areas of variability that the present grid infrastructures and management paradigms cannot adapt to efficiently. The study in the varying part of the load compared to the base load also underscores the urgent need for more effective predictive models and responsive grid management systems. Despite the numerous contributions made to knowledge, the current study has several limitations. The simplistic models used to determine the performance of the grid and the activities of the renewable energy production expose the assessment to vast variabilities and complexities rendering it more diverse than reality. Given that the paper only explores the technical perspective, it overlooks potential economic, regulatory, and social factors that significantly influence the effectiveness of renewable energy variation in power systems. Finally, the restricted period of study, 24 hours, is insufficient to generate an inclusive model that encompasses the broader annual and seasonal variation in both the load demand and the renewable power generation effort.

The findings of this study open multiple research directions of utmost impotence for improving power systems and supporting a transition to more sustainable energy systems. Specifically, future research should focus on developing and verifying more sophisticated models that can accurately simulate the dynamics of modern power systems, including variation of power produced by renewable sources and the effects of newly emerging technologies and grid management methods. There is also a significant need for empirical research utilizing the models and simulations discussed above in more practical contexts to validate them and improve our understanding of the practical benefits and drawbacks associated with replacing nonrenewable sources of energy with renewable ones. Moreover, the identified research gaps also involve understanding how the above-mentioned technological developments relate to other aspects of power system planning and managing, such as economic, regulatory, and social dimensions. Therefore, future research should focus on how these developments and changes in regulatory and consumer behavior could influence the potential and benefits of transitioning to the renewables.

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