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Chronological simulation and Quantitative Evaluation of System Reliability in a Complex Restructured Power System

Abstract:

Ensuring the provision of high-quality and dependable power supply to customers stands as a paramount responsibility within the realm of power systems. The concept of restructuring the power system emerges as an efficient approach to deliver economically viable and uninterrupted power supply. The assessment of power system reliability hinges on various factors, with the reliability index serving as a pivotal metric, dependent on both system security and adequacy. To enhance the reliability index, strategically locating FACTS devices becomes essential, a task facilitated through power flow analysis with specified constraints, pinpointing the weakest points through Genetic Algorithm-driven fast-acting device placement. The correlation between DG establishment and the reliability index was meticulously calculated, further bolstered by the introduction of a Derated Forced Outage Rate for enhanced performance assessment. In the pursuit of heightened power system reliability, sequential simulations prove invaluable, particularly in minimizing Expected Energy Not Supplied (EENS) and improving overall system reliability. The results obtained through sequential simulations underscore the effectiveness of this approach within bulk electrical systems. The installation of multiple FACTS devices in the system's weakest areas facilitated EENS computation, coupled with the assessment of related reliability indices such as system frequency and system duration. This approach not only enhances system reliability but also promotes the economic operation of both transmission and distribution. The simulation results substantiate the alignment of power system reliability objectives in deregulated power systems with the required standards, advocating for the restructuring of power networks. The reliability assessments, driven by the optimal placement of DGs and FACTS devices, reveal substantial improvements in system reliability, underscoring the pivotal role of these technologies in enhancing overall power system dependability.

1. Introduction:

In today's energy landscape, the deregulation of power systems has become a common practice to promote competition and efficiency. However, as power systems evolve into complex, interconnected networks with multiple stakeholders, ensuring their reliability remains a paramount concern [1]. The evaluation of the reliability of a complex deregulated power system has emerged as a critical research area. This multifaceted task involves assessing various aspects, including the robustness of the grid against unforeseen events, the adequacy of generation and transmission infrastructure, and the effectiveness of market mechanisms in maintaining grid stability [2]. Researchers and industry experts are continuously working to develop advanced methodologies and tools to comprehensively evaluate the reliability of these intricate power systems, taking into account both technical and economic factors.

One of the key challenges in evaluating the reliability of deregulated power systems is striking the right balance between market-driven decision-making and the need for system security. Market forces influence generation investment decisions and dispatch strategies, but they must also align with the grid's capacity to withstand disturbances and maintain reliable operations. Achieving this balance requires the development of innovative reliability assessment frameworks that consider the dynamic interactions between market participants, grid operators, and regulatory bodies [3]. Furthermore, as renewable energy sources and distributed generation play an increasingly prominent role in these systems, their intermittent nature adds an additional layer of complexity to reliability assessments. Therefore, ongoing research and collaboration among stakeholders are crucial to address these challenges and ensure the continued reliability of complex deregulated power systems [4].

In the context of the restructured power system, the generation segment has been subdivided into generating companies (GenCo's), the transmission sector into transmitting companies (TransCo's), and the distribution sector further divided into distribution companies (DisCo's). This transformation involved the privatization of these companies, with regulatory authorities and system operators overseeing their operations. Among these entities, the transmission system operators (TSO's) hold the responsibility for tasks such as managing transmission contingencies and assessing power transfer capabilities [5]. Deregulation has empowered customers with multiple choices, allowing them to select service providers based on economic considerations. Consequently, a customer's electricity bills are influenced by at least two entities, namely the transmission and distribution companies [6]. The primary objective of this unbundled power system is to efficiently and economically deliver electrical energy to consumers.

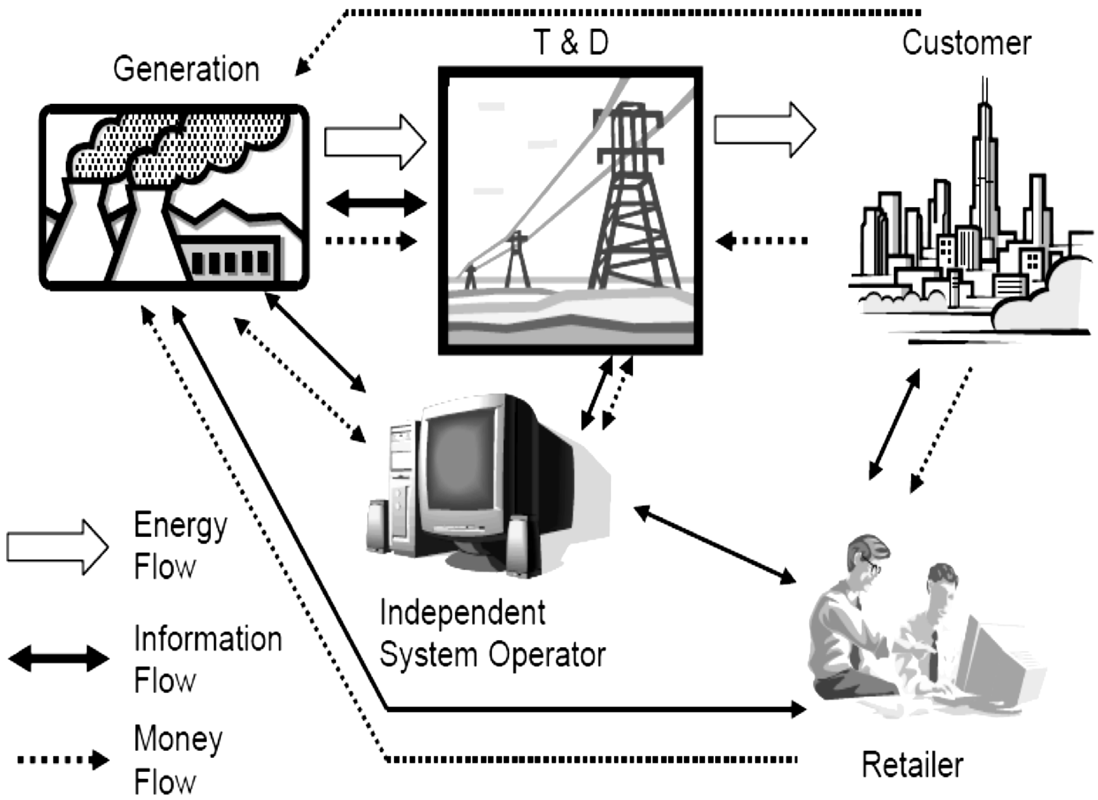

Figure 1. Structure of a Deregulated Power System

Figure 1 depicts the typical layout of a restructured power system, highlighting the roles of system operators and retailers. In a vertically integrated system, customers receive a single electricity bill, whereas in a deregulated system, separate electricity bills are issued for each sector, including generation, transmission, and distribution [7]. The Independent System Operator (ISO) assumes a crucial role in this framework, exercising control over pricing in each sector, regulating aggregators, and meticulously monitoring transactions across various entities.

The traditional power system network has undergone a transformation into a deregulated or restructured power system. In this restructured power system, regulations are decentralized, and oversight is conducted by Independent System Operators (ISOs) [8]. Numerous methodologies have been developed to address power system stability and transient stability within this restructured framework.

Within the electricity markets, aggregators operating within transmission and distribution companies play a pivotal role in regulating tariff details. The reliability and stability of the restructured power system are managed through the application of reliability and steadfastness indices [9]. These indices have been devised to assess interruptions and the duration of failures, both in the conventional power system and in the restructured one. Furthermore, the implementation of Flexible AC Transmission System (FACTS) devices has been instrumental in enhancing power system reliability. Each FACTS device possesses unique properties that contribute to the overall improvement of power system dependability. Reliability studies in the context of transmission expansion within the deregulated power system encompass the integration of solar parks and windmills [10]. The inherent uncertainties in system balancing and power system stability necessitate a comprehensive examination of the restructured system through reliability assessments.

Incorporating environmental considerations inherent to decentralized systems becomes pivotal in verifying system reliability within the broader network of bulk power systems [11]. This evaluation takes into account the nature and duration of uncertainties present in the deregulated power network, categorizing them and proposing corresponding recovery methods to enhance performance reliability within the test system. Addressing the flexibility of expansion within the restructured power system and the associated failure rates at individual nodes is achieved through the application of fuzzy logic [12]. This approach aims to stabilize these factors, mitigating the complexities associated with line flows and bus flows in the deregulated power system. Moreover, the short-term and long-term uncertainties arising from the presence of solar parks and wind energy are strategically managed through comprehensive short-term and long-term planning efforts within power system planning.

Optimizing the control modes of Flexible AC Transmission System (FACTS) devices is crucial to minimize remedial action costs, enhance system adequacy, and improve system availability. By fine-tuning these control modes, it becomes possible to reduce load curtailment, prevent blackouts, and minimize interruptions in the power system [13]. This optimization relies on state estimation algorithms and phase measuring units, which are linked to FACTS devices through a Supervisory Control and Data Acquisition (SCADA) system.

The integration of state estimation algorithms and phase measuring units is specifically designed to bolster power transmission capabilities and enhance overall system stability [14]. Within the test system, various FACTS devices such as Static Synchronous Series Compensators (SSSC), Thyristor-Controlled Series Compensators (TCSC), and Static Compensators are employed to analyze power transmission efficiency and system stability. Voltage source inverters used in FACTS systems are meticulously controlled by phase measuring units, which detect changes in electrical parameters relative to phase angle variations [15]. To identify the optimal position or setting for the installation of different types of FACTS devices, a dual search method is employed, ensuring their effective deployment within the power system.

2. Mathematical Expression:

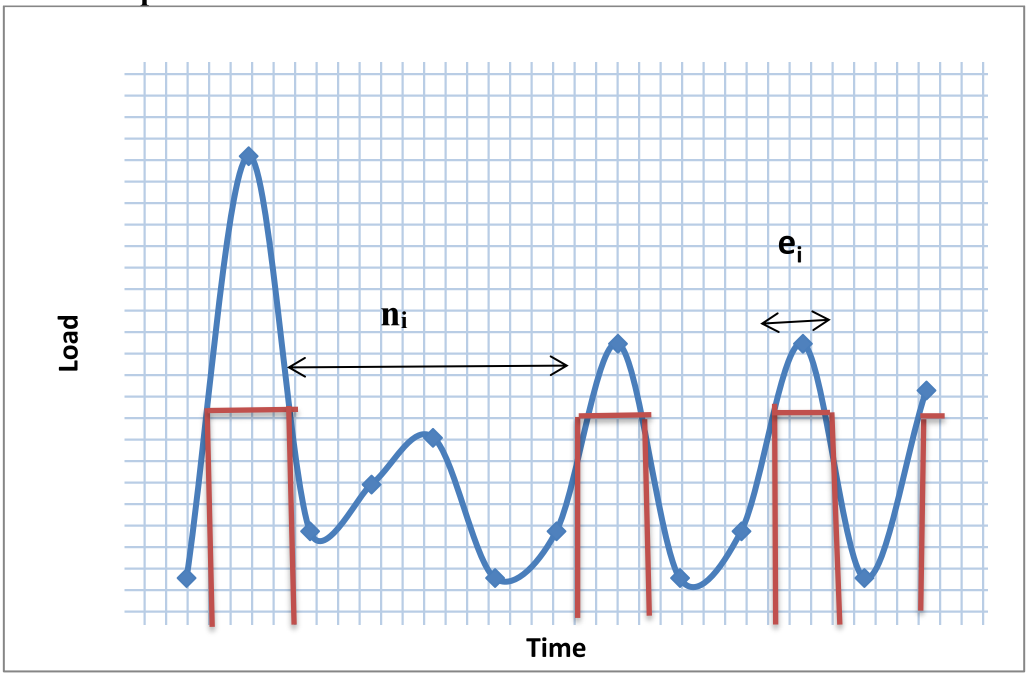

Figure 2. Time-Based Load Model

Let,

n_i – normal load pattern

e_i – extreme load pattern

N – average duration of normal load

A – average duration of extremis load

λ_{avg} – average component failure

λ – failure rate at normal condition

λ^1 – failure rate at extremis condition

Let's examine two components functioning under standard and extreme conditions, linked to their respective failure and repair rates.

Normal State Extremis State

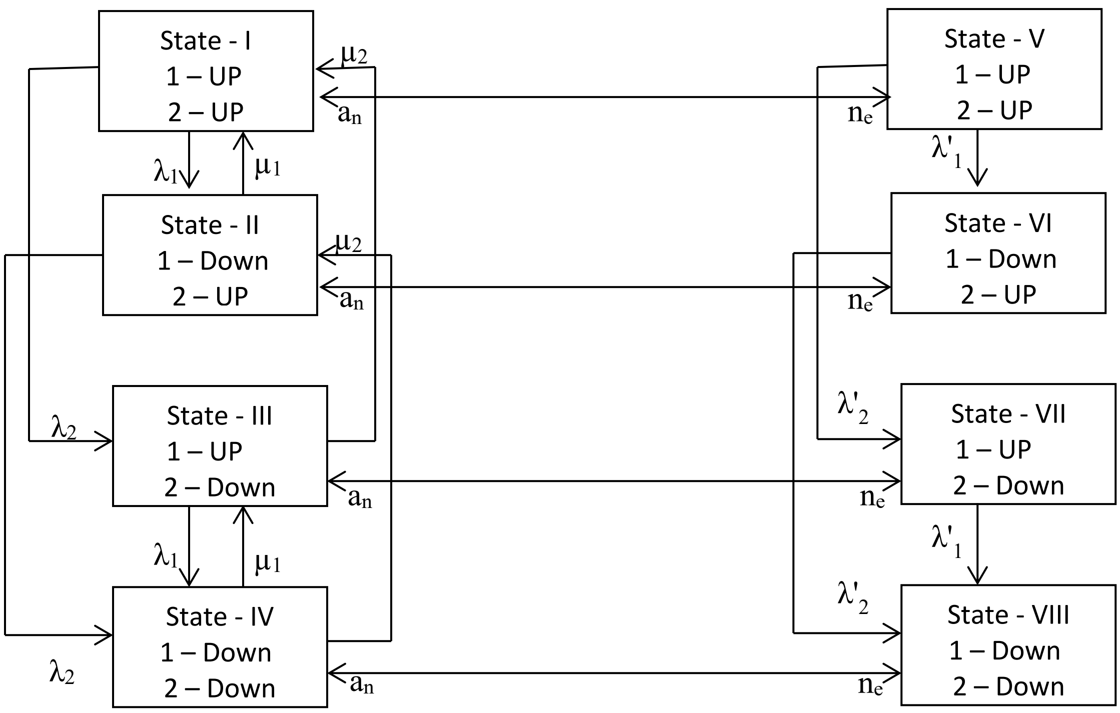

Figure 3 State space diagram of 2-Component, 2-State system

From the above state space diagram,

$$(\lambda_1 + \lambda_2 + n_e)P_I - \mu_1 P_{II} - \mu_2 P_{III} - a_n P_V = 0 \quad (1)$$

$$(\lambda_2 + \mu_1 + n_e)P_{II} - \lambda_1 P_I - \mu_2 P_{IV} - a_n P_{VI} = 0 \quad (2)$$

$$(\lambda_1 + \mu_2 + n_e)P_{III} - \lambda_2 P_I - \mu_1 P_{IV} - a_n P_{VII} = 0 \quad (3)$$

$$(\mu_1 + \mu_2 + n_e)P_{IV} - \lambda_2 P_{II} - \lambda_1 P_{III} - a_n P_{VIII} = 0 \quad (4)$$

$(\lambda'_1 + \lambda'_2 + a_n)P_V - n_eP_I \quad = \quad 0 \qquad (5)$

$(\lambda'_2 + a_n)P_{VI} - \lambda'_1 P_V - n_eP_{II} \quad = \quad 0 \qquad (6)$

$(\lambda'_1 + a_n)P_{VII} - \lambda'_2 P_V - n_eP_{III} \quad = \quad 0 \qquad (7)$

$a_nP_{VIII} - \lambda'_1 P_{VII} - \lambda'_2 P_{VI} - n_eP_{IV} \quad = \quad 0 \qquad (8)$

The dependent simultaneous equations are solved by

$P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 \quad = \quad 1 \qquad (9)$

The above linear equations can be expressed in matrix form

$$[D][P] = 0 \qquad (10)$$

Here, [D] is derived from the state-space diagram, and [P] is derived from the transpose of the independent equation. The matrix [P] represents the probability of failure rates for the evaluated components. The Expected Energy Not Supplied (EENS) can be calculated based on these probability of failure rates..

[D] =

$$\begin{bmatrix} \lambda1+\lambda2+ne & -\mu1 & -\mu2 & 0 & -an & 0 & 0 & 0 \\ -\lambda1 & \lambda2+\mu1+ne & 0 & -\mu2 & 0 & -an & 0 & 0 \\ -\lambda2 & 0 & \lambda1+\mu2+ne & -\mu1 & 0 & 0 & -an & 0 \\ 0 & -\lambda2 & -\lambda1 & \mu1+\mu2+ne & 0 & 0 & 0 & -an \\ -ne & 0 & 0 & 0 & \lambda'1+\lambda'2+an & 0 & 0 & 0 \\ 0 & -ne & 0 & 0 & -\lambda'1 & \lambda'2+an & 0 & 0 \\ 0 & 0 & -ne & 0 & -\lambda'2 & 0 & \lambda'1+an & 0 \\ 0 & 0 & 0 & -ne & 0 & -\lambda'2 & -\lambda'1 & an \end{bmatrix}$$

$[P] = [P_I \quad P_{II} \quad P_{III} \quad P_{IV} \quad P_V \quad P_{VI} \quad P_{VII} \quad P_{VIII}]^T$

The calculation of the Expected Energy Not Supplied (EENS) is based on load curtailments, along with the corresponding average frequency and duration index. This is expressed in the equation (11)

$$EENS = \sum_i^n CL_iF_iD_i \quad \text{MWhr/Yr} \qquad (11)$$

IEEE has introduced a variety of reliability indices for intricate systems, collectively referred to as bulk reliability indices [16]. The bulk Expected Energy Not Supplied has been adjusted in consideration of the annual peak load, as detailed in the equation (12)

$$BEENS = \frac{EENS}{P_L} \quad \text{MWhr/MWYr} \tag{12}$$

Reliability of bulk system with respect to the availability of supply is given as

R_B = 1 – Loss of Load Probability (13)

The reliability index for the bulk system with the variation of demand with respect to the time is given in the equation (14).

$$R_B = \frac{1}{\sum_{i=1}^{N} T_i} \sum_{i=1}^{N} P_i(1 - LOLP)T_i \tag{14}$$

Here T represents the time interval of i^{th} Component in the reliability test system.

P_i represents the probability of failure rate of i^{th} Component in the reliability test system

The Loss of Load Probability can be approximated by considering fluctuations in supply and demand, as well as changes in load patterns [17]. Unserved energy indicates a lack of alignment between generating capacity and load patterns, with these patterns varying across different demand time intervals..

Therefore, the Loss of Load probability can be identified from the generating units and it is given in the equation (15)

$$\text{LOLP} = \sum_{i}^{N} P_{C_i} > L_i \tag{15}$$

P_{C_i} Stands for the probability of load curtailment with respect to the load pattern correlated with the capacity of generating units.

The independent generating units which are required to reduce the forced outage rate and the probability of the failure rate can be estimated with the unavailability index and it can be written as

$$P_{C_i} = U_i\,(1 - U_i) \tag{16}$$

Where U_i represents the Unavailability index in the bulk reliability system with the independent generator units.

The availability function of the bulk reliability system is denoted as A_i with the i^{th} component and system can be represented as in equation (17)

$$A_i(L_i, T_i) = \frac{1}{\sum_{i}^{N} T_i} \sum_{i}^{N} A\,(L_i)T_i \tag{17}$$

The availability index can be calculated with the variations of outage rate in the load pattern

3. Evaluating Bulk Electrical System Reliability through Chronological Simulation

Chronological simulation offers a versatile approach to assessing the reliability of bulk electrical systems, regardless of their forced outage rates [18]. To determine adequacy and system security, it is essential to calculate delivery point indices derived from generalized frequency and interruption indices. System adequacy indices help quantify blackout magnitudes and their corresponding durations in relation to network parameters [19].

Within this closed-loop simulation, changes in frequency and voltage magnitudes are closely monitored, alongside the influence of power system stabilizers, which play a significant role in ensuring power system reliability within the context of deregulated power system networks [20]. Transmission and distribution networks' behavior during contingency and overload situations is overseen by both transmission system operators and independent system operators. Sequential simulation directly impacts electricity markets, as bulk interruption indices provided by transmission and distribution companies are correlated with financial parameters managed by aggregators in power exchanges. This correlation informs decisions related to electricity market operations and sales [21].

4. Identifying Transmission Weaknesses in Complex Systems

In evaluating the holistic performance of the revamped power infrastructure, it becomes crucial to pinpoint and rectify shortcomings in the transmission sector [22]. With an increased number of generating and distribution companies, the probability of congestion within the transmission network rises significantly [23]. Consequently, it is imperative to provide adequate compensation to mitigate these transmission deficiencies. Utilizing the principles of traveling wave theory, we can accurately locate faults and transient events along transmission lines. To identify transmission deficiencies, we propose a comprehensive set of analyses, encompassing Dynamic Analysis, Control Analysis, and Recovery Analysis [24]. Furthermore, this approach not only identifies deficiencies but also offers recovery strategies to enhance the existing system and bring it closer to the ideal configuration.

Installing DG's and FACTS together in a network plays a vital role in power loss and system adequacy. The system security and the reliability also analysed with the addition of FACTS devices in a network [25]. If the sources at the load side is increased by three units, the units will be encaged by DG's and the third Unit is installed with the FACTS devices. The minimisation function gives that the new sources can be installed at the busses 6, 4 and 2. At bus 6 and bus 4, DG's are installed and the Unified Power Flow Controller is installed in bus two. The modified power flow solution using Newton-Raphson method gives a tremendous reduction in power loss. The reliability index in the restructured power system can be verified with the inclusion of DGs. The interruptions can be calculated using the equation

Expected Energy Not Supplied (EENS)= $\sum_{j\epsilon M}(U_j P_j)$ (18)

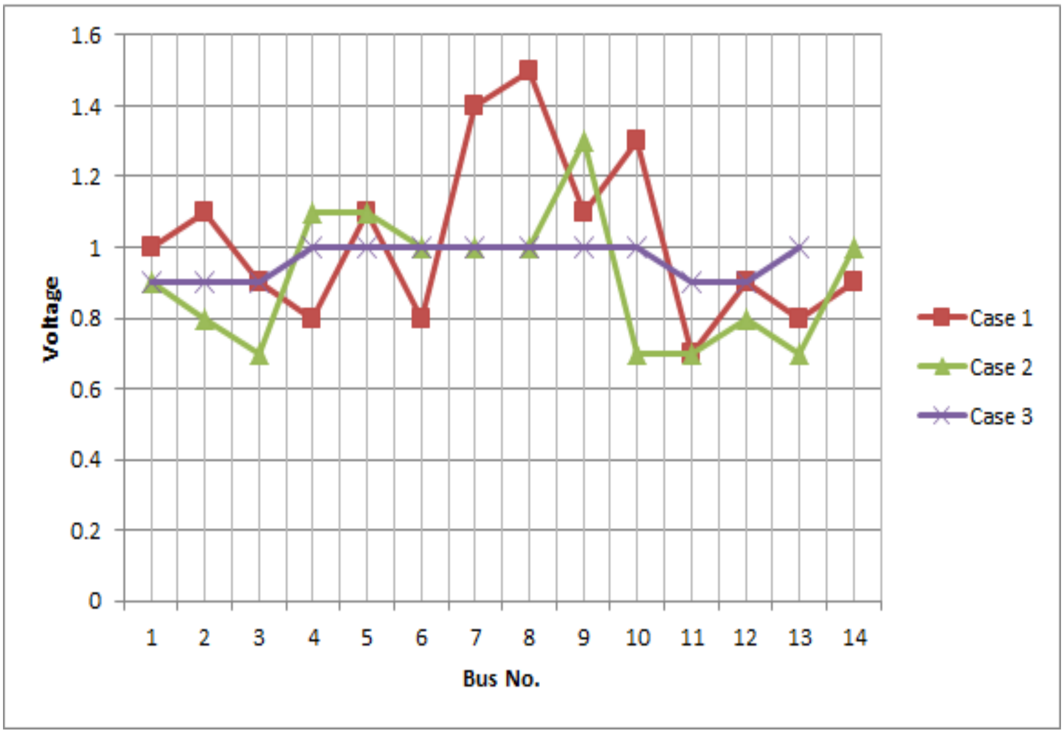

Figure 4: Voltage Profiles for IEEERTS bus System with DGs and FACTS

Conclusion

This paper primarily focuses on performance-based regulation within the bulk power system, employing sequential simulation to assess composite system reliability. Emphasis is placed on ensuring system adequacy and security as the key constraints for enhancing power system reliability in the context of a deregulated power system, particularly within electricity markets that incorporate Distributed Generators (DGs). An innovative approach is introduced for supervising power system networks, utilizing a combination of Distribution Generators and Flexible Alternating Current Transmission System (FACTS) devices. The proposed method centers around optimizing the placement of DGs and FACTS devices, with a particular focus on their ratings and locations. This optimization process is accomplished through the utilization of Genetic Algorithms, featuring a coding structure designed to facilitate mutations at precise locations. The algorithm operates seamlessly within a one-dimensional array framework. This study explores the impact of different Flexible Alternating Current Transmission System (FACTS) devices on the IEEERTS system and calculates the corresponding Expected Energy Not Supplied (EENS). Notably, the most minimal EENS was achieved when incorporating a Unified Power Flow Controller (UPFC) with finely tuned control settings. These findings shed light on the optimal placement of FACTS devices and their influence on the IEEERTS system. The assessment results hold significant potential for advancing the use of FACTS devices within renewable energy resources. They provide a valuable foundation for researchers seeking to identify suitable devices and determine their optimal installation locations.

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