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A Comprehensive Review on the Modern Power System Reliability Assessment

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Abstract- A power system is highly susceptible to system irregularities such as control failure, security system failure, instabilities, and inadvertent human errors. Ensuring the reliability of the power system is vital for assuring the quality of the power supply by taking definite steps to safeguard against probable events that involve an element of risk. The application of reliability assessment techniques helps to guarantee reliability, thereby contributing to the better performance of the power system. The key objective of the reliability study is to predict and associate reliability indices for various reliability progress initiatives for network configurations. This comprehensive review presents the significance of reliability, reliability indices, various reliability methodologies, and supporting literature.

Keywords Reliability methodologies, System failure, Assessment Techniques, Reliability indices, Power quality.

1. Introduction

The Power system on the whole is exposed to random faults due to component failure, transmission problems, climatic conditions, etc., . So the vital task of a power system is to supply the power to the customers as economically and reliably as possible even when subjected to random faults. The Electric power utilities also face increasing uncertainty due to the administrative, commercial and societal constraints, as they have to effectively operate the existing system and also should plan for the enhancement with the ever increasing demands. All these surroundings have created an environment for the utility to design new facilities or to optimally utilize the existing system configuration with the enhanced system reliability and reduced operating cost. Power system reliability studies usually focus on various functional zones such as generation system, Transmission system, Distribution system, interconnected system, Protection system, Industrial and commercial systems. In general, power system reliability mostly addresses the issues of service interruption and power supply loss. Also many of the reliability studies have focused, in identifying the main reason behind the interruption and in handling the increasing demand[1]. Further, reliability is also defined as the probability of a device or system performing its assigned function adequately under the specified operational situations over time [2]. Power system reliability is usually represented by two aspects, namely adequacy as well as security. Adequacy considers stationary system situations, which relate to the presence of appropriate facilities in the system to fulfill the consumer demand [3],[4]. It is also appropriate to take into account of the scheduled and expected unscheduled outages of system components. On the other hand, system security relates to the capability of the system to endure sudden perturbations within it. Some of the disturbances are the electric short circuits or the sudden loss of system components from credible contingencies. The reliability study should not only analyse the existing infrastructure but also should consider the inclusion of new facilities and predict the risk of hazards which contributes to power outages along with the restoration stratagies [5]. In the current scenario, the reliability study also differs with respect to the entities considered in the deregulated environment such as generation companies, retailers, large consumers and system operators, since the challanges faced by these entities vary [6].Also, the integration of renewable energy sources and energy storage devices as distributed generation (DG) nearer to the load centers are increasing to meet the increasing demands, there is a deemed necessity to analyse the reliability and the risk assessment of these systems [7][8]. With the inclusion of DGs,self generating equipments and power electronic devices, the power quality issues and the reliability studies are also gaining importance [9][10]. Many research work has also been carried out on the mathematical models, reliability indices and approaches in the reliability studies, since the reliability study involves various statistical, probabilistic and analytical methods [11]. On the whole, an extensive study on the reliability analysis of different system and different mathematical models are inevitable.

The main contribution of this paper is to outline the effectiveness of reliability assessment in power systems, classification of reliability assessment techniques and various reliability indices used in reliability evaluation of power systems, and gives a lead to the future perspective in reliability. The highlights of the work is given below.

1. The assessment of reliability indices is carried out to support in identifying the interruptions. In addition, suggestions are provided for a proper reliability initiative to uphold the continuity of power supply.
2. The reliability assessment techniques based on deterministic, probabilistic, intelligent and simulation methods are discussed.
3. This study supports the identification of proper reliability assessment techniques for performance enhancement of electrical distribution networks.
4. The present review work has been explored with various reliability assessment methods in detail to fulfill power system requirements in reliable manner and most of the reviews emphasis on historical assessment and analytical approach.

The paper has been organized as follows: The reliability indices of various hierarchical levels of power systems are presented in section 2. The classification of various reliability assessment techniques and their significances are explained in section 3. Section 4 and 5 presents the summary and conclusions.

2. Reliability Assessment In Various Hierarchical Levels (Hl)

Reliability assessment of power systems is carried out by considering the following five necessary steps[12].

1. Data collection regarding the description of system configuration and load operating requirements.
2. Performance criteria based on system requirements and checking priorities of the system as per need.
3. Analysing the reliability indices of the system by considering a suitable analytical method.
4. Summarizing the failure effects and comparing them with simulation tools to assess real-time behaviour.
5. Predicting future power system operations and suggesting periodical measures for the better functioning of the system.

The adequacy-based reliability assessment methods in the power system are predominantly applied to various hierarchal levels, as shown in Figure 1. HL-I is concerned only with the adequacy of power generation to cope with the system load demand and frequently designated as generating capacity reliability evaluation. HL-II represents generation and transmission services utilizing a hybrid system [13].

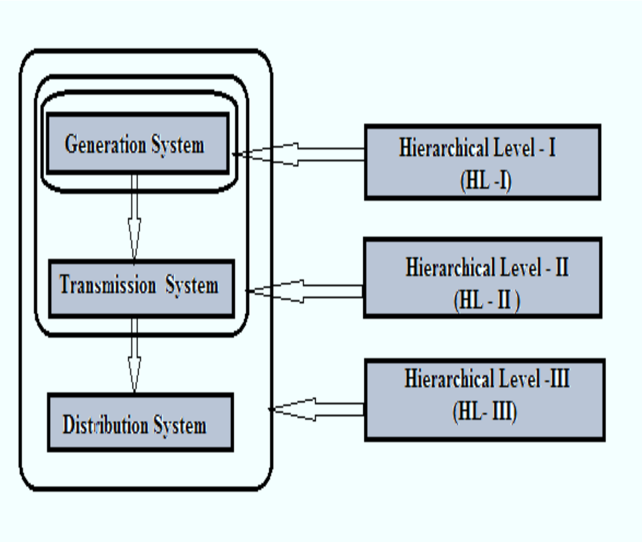

Figure 1: Hierarchical level representation of a Power system.

HL-III adequacy assessment consists of entire functional divisions to evaluate customer load point adequacies. Therefore, the evaluation of HL-III is termed a complete power system adequacy assessment. The reliability indices considered at each hierarchical level are substantially dissimilar to enumerate the reliability of the system. An overall reliability evaluation of the entire system cannot be carried out as a single problem due to its enormity and complexity, so the reliability of each sector is assessed individually. The generation and transmission system reliability indices play a major role in maintaining continuity and quality of power supply from generating stations to load dispatch centres.These indices are represented as Hierarchical level- I and II indices. An outage in the generation system will necessitate the removal of the generation unit either for repair or for replacement. Therefore, an outage in the system directly influences the reliability of the system. Availability and forced outage rate are the two terms representing the probability of success and failure of any event in the power system.

$$\text{Availability(AV)} = \frac{\text{Time period of the unit being in service}}{\text{Total Time considered for unit service}} \tag{1}$$

$$\text{Forced Outage Rate (FOR)} = \frac{\text{Sum of time unit is being out of service}}{\text{Total Time considered for unit service}} \tag{2}$$

$$\text{Loss of Load Expectation (LOLE)} = \sum_{i=1}^{n} t_i \ \text{p}_i \tag{3}$$

$$\text{Expected Demand Not Served (EDNS)} = \sum_{i=1}^{n} (\text{DNS}_i) P_i \tag{4}$$

$$\text{Expected Energy Not Served (EENS)} = \sum_{i=1}^{n} (\text{ENS}_i)\text{P}_i \tag{5}$$

$$\text{Loss of Load Probability (LOLP)} = \sum \frac{\text{P}_i \text{t}_i}{100} \tag{6}$$

$$\text{Loss of Energy Expectation (LOEE)} = \sum_{i=1}^{n} \text{Amount of Power not supplied to the Load} \tag{7}$$

The distribution system indices are characterized by basic reliability indices and several index-based reliability indices [14].The basic indices such as failure rate, average outage time and unavailability are calculated based on the failure rate of components, repair time and configuration of the system.

$$\text{Failure Rate } (\lambda) = \sum_{i=1}^{n} \lambda_i \tag{8}$$

$$\text{Annual Unavailability (U)} = \sum_{i=1}^{n} \lambda_i \ r_i \tag{9}$$

$$\text{Annual Outage Time (r)} = \frac{\text{U}}{\lambda} = \frac{\sum_{i=1}^{n} \lambda_i r_i}{\sum_{i=1}^{n} \lambda_i} \tag{10}$$

Service Related Indices:

The following indices helps to assess the performance of the system and to predict future load operations.

System Average Interruption Frequency Index(SAIFI)

$$= \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} = \frac{\sum \lambda_i N_i}{N_i} [\text{int/ yr}] \tag{11}$$

System Average Interruption Duration Index (SAIDI) =

$$\frac{\text{Total Number of customer interruption duration}}{\text{Total number of customers served}} = \frac{\sum \text{U}_i N_i}{N_i} [\text{hrs/ yr}] \tag{12}$$

Customer Average Interruption Frequency Index (CAIFI) =

$$\frac{\text{Total Number of customer interruption}}{\text{Total number of customers Affected}} = \frac{\sum \lambda_i N_i}{N_a} [\text{int/yr}] \tag{13}$$

Customer Average Interruption Duration Index (CAIDI) =

$$\frac{\text{Total Number of customer interruption Durations}}{\text{Total number of customers interruptions}} = \frac{\sum \text{U}_i N_i}{\sum \lambda_i N_i} [\text{hrs/int}] \tag{14}$$

Average System Availability Index (ASAI) =

$$\frac{\text{Customer hours available in service}}{\text{Customer hours demanded}} = \frac{\sum 8760 N_i - \sum \text{U}_i N_i}{\sum 8760 N_i} \tag{15}$$

Average System Unavailabilty Index(ASUI)

$$= \frac{\text{Customer hours not available in service}}{\text{Customer hours demanded}} = \frac{\sum \text{U}_i N_i}{\sum 8760 N_i} \tag{16}$$

Average Energy Not Served (AENS) =

$$\frac{\text{Total energy not supplied}}{\text{Total number of customers served}} [\text{kWh/ yr}] \tag{17}$$

The above indices reflect the network's performance, the configuration of components, protection coordination, operating strategy and other functions. The modern electric power system constantly undergoes many transformations due to several commercial and environmentally friendly initiatives[15],[16]. The rapidly growing power demand can be addressed by deploying a DG established by Distributed Energy Resources(DER) like solar energy, wind power, mini-hydro power plants, etc. A microgrid can be designated as an assembly of interrelated loads and DER that turn into a particular manageable unit, bound and detach from the grid. Microgrids are categorized as AC microgrid, DC microgrid and hybrid AC/DC microgrid. A microgrid can function in dual approaches, namely, grid-connected mode as well as islanding mode. Integration of the microgrid in distribution systems affords adequate power supply, unpolluted energy, operation and stability improvement of the regional electric grid, reliability enhancement and resilience. The primary function of DG is to produce power for load requirements or under any fault occurrence [17],[18]. The various researchers has studied the significance of optimal integration of DGs into electric distribution network and their performance [19]. As the renewable based DGs are subjected to uncertainties, various fundamental methods used in handling uncertainty parameters in distribution systems and their impact of integration on the reliability are also analyzed [20].An overview of asset management systems and other features such as the structural design, components, purposes, fault investigation and risk supervision were also presented in [21]. The microgrid applications, challenges, reliability, resilience with electrical grids were discussed in [22]. The overall performance of the power system connected either with microgrid or with Distributed Generation sources is generally assessed using the indices SAIFI, ASAI and ASUI.

3 Reliability Assessment Methods of Power Systems

Reliability assessment techniques helps to analyze the complex conditions in power systems and enhance the quality of service for the system's operations. The reliability calculation methods are classified into deterministic, probabilistic and intelligent methods, as shown in Figure 2. Many researchers have adopted these methods, and the simulation tools supporting reliability studies have also been analyzed in many research works. An overview of these methods has been discussed below:

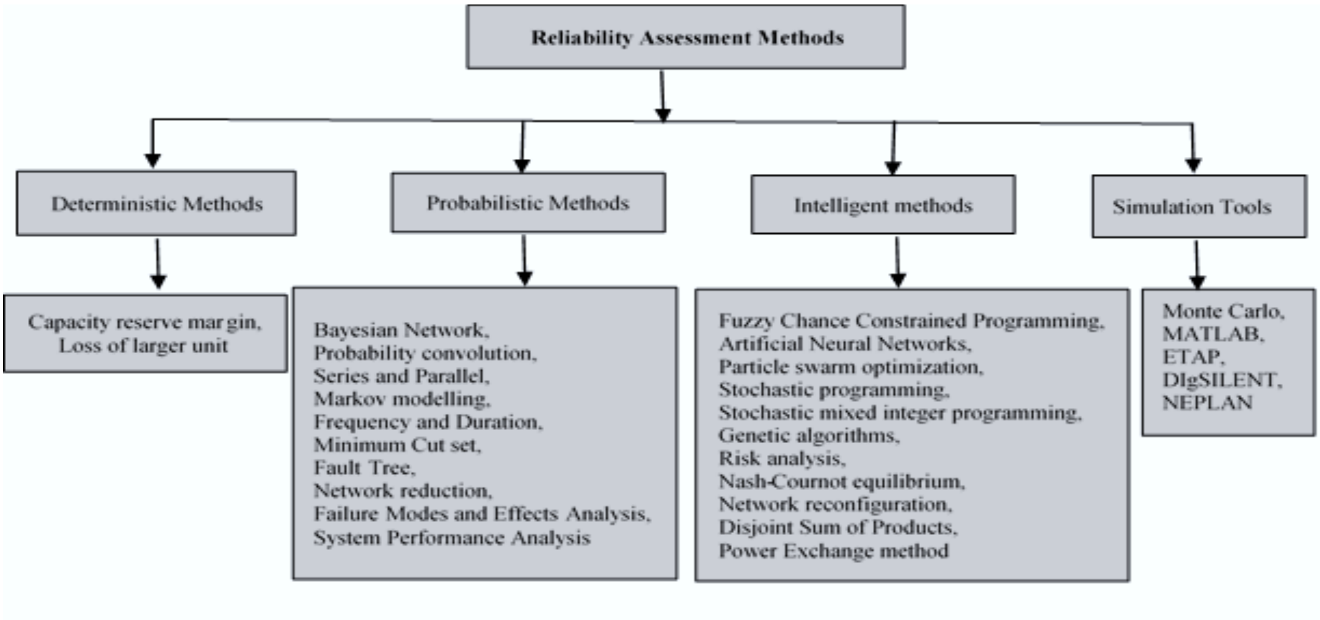

Figure 2: Representation of Reliability Assessment Methods.

3.1 Deterministic Methods

The deterministic method supports the assessment of system reliability with only fewer faults and cannot forecast the chances of risk. The most commonly used deterministic techniques are loss of larger units and capacity reserve margin. The reliability characteristics of Sri Lankan power generation based on optimal reserve capacity margin planning was explained using the WASP IV tool. The reliability indices of various generation units such as reserve margin, LOLP and unserved energy were presented [23].

3.2 Probabilistic Methods

The probabilistic method evaluates the possibility of several events over the risk indicator and statistical standards. It is observed that the probabilistic methods are more effective than the deterministic methods. Many of the reliability approaches adopt the probabilistic approach as compared to the deterministic approach. The elementary methods of probabilistic risk assessment are the analytical method and simulation method. The analytical methods are series and parallel networks, probability convolution, Bayesian network, state-space (Markov process), frequency and duration, faulty tree etc. The frequently employed simulation method is the Monte Carlo method. In this method, the random behavior of the system is analyzed through simulation of physical relationships. The Bayesian network supports analyzing the uncertainties in various system functions and helps review component reliability at its initial design stages. Based on the Bayesian network approach, various reliability factors of an urban distribution system in China were analyzed by applying a conditional probability approach to the probabilistic behavior of different components [24]. The convolution method analyses the system with reduced variables, which eases the computation but is not adequate for a system with a multivariable function. Based on the failure approach, the network method is applied to control the series or parallel connection, and the reliability index can be measured using the failure and normal states. Markov modelling helps model power system operations with dependent failure and repair models and evaluates reliability and availability analysis for any complex system with constant failure and repair rates.

The frequency and duration method helps to calculate generation reliability measures such as availability of load, frequency of transitional states, meantime of standby states, cumulative states of the specified system, standby conditions and outage duration. Based on the Markov chain, frequency and duration concepts, reliability adequacy assessment of IEEE 6 Bus system were presented [25]. Minimal cut sets are used to identify single point failure of the system, but it is not effective when applied to the complete system. Also, if the cut set is more extended, it means the vulnerability will be less. A novel framework based on minimum cut set theory has been presented to estimate the accessibility of DC microgrids [26]. The fault tree approach provides a logical representation of the states of the system in terms of failure states for the components. The reliability assessment of a 132 kV transmission line in Northern Nigeria was evaluated by fault tree analysis, and the performance of various protection equipment was analyzed [27].

Failure Modes and Effect Analysis (FMEA) technique supports the analysis of component failures and helps identify the resultant effect on system operation. This methodology supports the early identification of single failure points, critical system and system interface problems that influence security. Reliability assessment of RBTS Bus-2 based on FMEA approach and Monte Carlo simulation technique was explained in [28].The reliability analysis of RBTS Bus-2 by considering the presence of various protective devices and alternative supply was presented [29]. The reliability analysis of the distribution system of the Indian Institute of Technology, Roorkee, was presented using the FMEA technique [30]. Reliability assessment of IEEE RBTS Bus-2 with Distributed Generation was synthesized based on the FMEA method, and reliability indices with different conditions were synthesized by Monte Carlo simulation [31]. The system Performance Analysis technique helps to analyze the interruption rate of the load and its consequences. Based on performance analysis technique, Omassery utility feeder reliability analysis of Calicut, Kerala with the impact of Distributed Generation was analyzed [32]. The reliability analysis of a domestic distribution network and summary of the comparative distribution system reliability indices with and without DG was presented [33]. A systematic study of reliability analysis was explained employing system indexes and two contrast indexes. The seven customer indexes are Reliability Probability (RP), Average Temporary Interruption Duration (ATID), Average Sustained Interruption Duration (ASID), Average Interruption Frequency (AIF), Equipment Shutdown Frequency (ESF), Repeated Interruption Probability (RIP), voltage Eligibility Rate (VER).

In contrast, the contrast indexes are changes in reliability probability (ΔRP) and Difference in interruption frequency (ΔIF). Ten 10kV distribution networks in the Guangdong power grid and their respective customers' data were considered, and reliability indices were analyzed [34]. Reliability assessment based on the performance analysis was presented for an electrical distribution network with a 33kV feeder in the Nellore substation in Andhra Pradesh [35]. A Composite Reliability index (CRI) was defined to represent the overall reliability of substations in the renewable energy penetrated power system. By considering Central Electricity Authority of India data from 2015 to 2016 and Maharashtra MAHADISCOM data in 2018, the overall reliability of different substations and CRI were computed [36]. Reliability indices such as SAIFI, SAIDI, CAIDI, ASAI and CAIFI, of two electricity distribution networks in Ahoada and Egi in Rivers state, Nigeria, were studied [37]. Reliability evaluation of a radial system with the total load capacity of 4025 kW consisting of four load points with 2025 customers and Distributed generator of 1500 kW was presented, and the significance of DG integration was explained [38].A reliability index was introduced for an active distribution network, which explained the characteristics of the analytical method [39]. Based on performance analysis, an overall reliability assessment of the Abuja municipal city network was presented in SAIFI, SAIDI and CAIDI [40]. The reliability assessment of Kaduna and Kano distribution systems was carried out based on performance analysis of reliability indices such as SAIDI, SAIFI and CAIDI [41]. Reliability assessment of the Omdurman electric distribution network was undertaken by performance analysis and indices such as SAIFI, SAIDI, CAIDI, MAIFI, CTAIDI for 33 kV and 11kV lines. The findings of the study were summarized [42]. Weibull distribution is widely used to characterize the probabilistic behavior of the system to analyze life data and assess failure time through scale and shape parameters. The exponential distribution is mainly used for revealing the behavior of a system with a constant failure rate. The reliability assessment of a hybrid system based on Weibull distribution and the Exponential distribution were analyzed by considering the RBTS Bus 6 system. The reliability indices were presented with various types of failure rates [43].

3.3 Intelligent Methods

Various intelligent techniques such as credibility theory, Fuzzy Chance Constrained Programming (FCCP), Artificial Neural Networks, Particle swarm optimization, Stochastic programming, Stochastic mixed-integer programming, Genetic algorithms, Risk analysis, Systematic Human Error Reduction and Prediction Approach, Nash-Cournot equilibrium, Network reconfiguration, Disjoint Sum of Products and Power Exchange method are used in the reliability analysis of power systems.

Credibility theory can combine objective as well as subjective uncertainty by integrating stochastic and fuzzy approaches. A hybrid algorithm explained the reliability evaluation of the distribution system. The algorithm is based on fuzzy simulation and FMEA technique to the IEEE test system, including 67 nodes and 38 load points [44]. Fuzzy Chance Constrained Programming (FCCP) provides resources in permitting the decision-maker to reflect goals in terms of the possibility of their attainment and supports reliability index calculations. The reliability assessment of the distribution system employing appropriate fuzzy membership functions with the rule was discussed in [45]. In addition, the reliability assessment of the IEEE RBTS Bus 2 system was presented in [45]. An optimization method built on FCCP was introduced for reliability index evaluation. By applying the FMEA-based fuzzy approach, the frequency of equipment failure rate in the microgrid reliability estimation was studied [46]. The reliability assessment of the Devanur substation was presented based on fuzzy value analysis [47]. Artificial Neural Networks (ANN) supports the investigation of various system conditions such as standard, faulty and overload by providing the best configuration of the neural network through proper training. Artificial Neural Network-based reliability evaluation technique was introduced, and the reliability assessment of North Taiwan was computed and compared with an analytical method like the Probability and Frequency network method [48]. Particle swarm optimization supports assessing the estimated load growth, failure statistics, cost of renewable energy sources, proper placement of energy sources and voltage profile improvement. The particle swarm optimization algorithm was proposed to handle different kinds of uncertainty conditions of distributed generations and was applied to the IEEE 34-Bus system [49]. A framework for optimal power dispatch in interconnected microgrids has been explained based on reliability and market operation aspects. The uncertainty in microgrid components was analyzed using the particle swarm optimization algorithm and compared with the Monte Carlo simulation method [50]. An optimization process for the reliability enhancement of microgrids based on the PSO with Monte Carlo simulation has been presented [51]. A linear optimization method based on load curtailment of microgrids was proposed and applied to RTS and RBTS, and also the probability of load curtailment analysis was presented[52]. A logical and optimized approach based on reliability and supply-security objectives for microgrids was explained in [53]. Clustering techniques for scheduling a stand-alone microgrid with the day-to-day configurations of wind and load profiles were proposed. An analytical idea for reliability estimation of battery energy storage system was developed, and reliability indices such as FOR, LOLE, LOEE of various scenarios were analyzed [54].Stochastic programming aids in obtaining optimal decisions for solving the uncertainties of load operations, cost analysis of utility grid, and integration issues of renewable energy sources. A risk-controlled stochastic programming framework and several microgrid risk management strategies were analyzed using Monte Carlo simulation[55]. The stochastic mixed-integer programming technique was used to analyze supporting performance enhancement of domains such as protection and security under uncertainty. A stochastic mixed-integer programming model was presented for the performance enhancement of microgrids. A set of intelligent port indexes for the microgrid planning process improves the system's smartness, and various case studies were discussed in [56]. A risk-centered decision-building outline framed as a double-stage stochastic programming problem has been presented to calculate the uncertainties in wind production and Distributed energy resources [57]. Genetic algorithms help in defining the realistic objective functions or reliability of the system's performance enhancement. An objective function was suggested to curtail the operational cost of microgrids with extensive plug-in electric automobiles, and reliability indices of the economically optimized microgrid were proposed [58].

A probabilistic generation-load model with a large number of probable working conditions of renewable DG units and their probabilities were explained in [59]. Temporal and annual indices of voltage outline and line flow correlated attributes such as Risky Voltage Down (RVD), Risky Voltage Rise (RVR), Interest Voltage Rise (IVR), Line Loss Increment (LLI), Line Loss Reduction (LLR) and Line overload flow (LOF) were introduced and implemented on 4-Bus and IEEE 33- Bus radial distribution systems [59]. Risk analysis supports the minimization of power outages, supply restoration of the system and provides future estimates for the system's operations. Two crucial risk evaluation methods, namely value at risk and conditional value at risk, were used to forecast the power at a particular level of risk in generation for various scenarios generated by using the Monte Carlo method [60]. An integrated framework for risk-based performance analysis of microgrids with DG and energy storage, including the dynamic grid assessment of energy, power supply and protection, as explained in [61]. An optimum power dispatch concept considering risk management using Model Predictive Control (MPC) was explained [62]. A systematic method to assess the risk condition of isolated microgrids in Dynamic Secure Region (DSR) was proposed, and the effectiveness of the DSR assessment method was analyzed [63]. The risk reduction technique associated with DER maintenance was explained, and the reliability indices of a real-time system were presented [64]. Risk assessment methodology defined by NERC Standard, CIP- 014-1 on Physical Safety of Distributed Generation resources and its risk influences were summarized [65]. A series of new metrics, namely trade and industry indices and value risk indices, was proposed to analyze microgrid planning and operation [66]. Various perspectives on advanced risk assessment methods of power systems and many case studies were discussed[67]. A risk assessment approach was presented for improving power supply resiliency from the outlook of economic and power supply readiness, which were considered vital decision factors in power systems [68]. A mathematical model to handle risk conditions of a grid-connected microgrid was discussed in [69]. Systematic Human Error Reduction and Prediction Approach (SHERPA) helps identify human operation errors, designing errors and functional errors of the system. Novel methodologies were proposed for risk analysis of human error concerning user experience of interactive systems based on a hybrid approach of SHERPA, FMEA and Fuzzy TOPSIS. The risk investigation of human inaccuracies concerned with the communication of design was summarized in [70]. Nash-Cournot equilibrium indicates each electricity market participant's profit-maximization objective and represents the clearing conditions of non-smooth demand functions of the real power of the electricity market.

A two-stage stochastic game model through the Nash-Cournot Pricing mechanism and conditional value-at-risk criterion were explained to describe the payoff function of each microgrid, and various risks of overcommitting energy supply with security problems were discussed [71]. The network reconfiguration techniques support enhancing the system reliability. The performance indices for three different kinds of distribution systems, i.e., meshed, radial and a superior kind of network titled as "flower" network, were discussed through Windows-built interactive software. Using RBTS Bus-2 Feeder-1 and Singapore power distribution network, reliability indices were enumerated, and it was concluded that the flowering network provided better reliability than other networks [72]. The importance of network reconfiguration technique based on reliability assessment was explained by using RBTS Bus-2, and effects of reconfiguration of various load points of the feeders were presented in [73]. The disjoint Sum of Products algorithm supports reducing computation time using the direction of the implementation time using 2^{2P-2}. P represents the number of paths and practices path set enumeration for system configuration analysis. Reliability evaluation of various substation bus bar arrangements was explained by the Disjoint Sum of Product algorithm using C/C++ software [74]. The power exchange method supports the enhancement of the reliability of the system and provides economic benefits. The power exchange algorithm was presented based on the customer interruption cost reduction and a microgrid-connected RBTS Bus-2 system [75].

3.4 Simulation Tools

Various simulation tools such as Monte Carlo, MATLAB, ETAP, DIgSILENT, NEPLAN were mainly used to explore the real-time performance of a power system. These tools mainly support in analyzing probabilistic behavior of the components under load operations and help to ascertain fault conditions of the system.

The Monte Carlo method is also known as the random sampling method and is categorized into sequential and non-sequential methods. They are mainly helpful in recognizing the influence of hazardous, ambiguous predictions and forecasting representations. Several simulation techniques such as Monte Carlo, discrete event, subset, hybrid subset, simulated annealing, stochastic, digital and Markov System Dynamics were applied for real-time reliability measures [76]. The reliability analysis of the Nigde region's electricity system based on the Monte Carlo Simulation (MCS) method was explained by estimating the performance indices for the system feeders and their load points [77]. FMEA method was applied on feeder 3 of Bus 6 of the RBTS load point, and system indices were calculated and compared with the MCS technique in the VC++ platform [78]. A simulation algorithm built on the cross-entropy method was demonstrated in addition to sequential MCS, and the reliability indices were calculated for time-dependent load for a grid-connected microgrid [79]. Reliability evaluation of a laboratory-based microgrid was explained using the primary system's well-being indices, which provide association among the deterministic and probabilistic methods [80]. An evaluation methodology with purely stochastic distributed generation simulation was discussed using islanded microgrids. The reliability indices were calculated using the MCS technique for the test system of idealized microgrid containing seven load points and one stochastic distributed generation [81]. An MCS-based algorithm used for computing the reliability indices on a sample radial distribution system with DG was discussed in [82]. A set of novel reliability indices such as Microgrid System Important Load Average Interruption Frequency Index (MSILAIFI), Microgrid System Important Load Average Service Availability Index(MSILASAI), Microgrid System Important Load Average Interruption Duration Index(MSILAIDI),Microgrid System Important Load Energy Not Service Index(MSILENSI) and Energy Storage Optimization Degree Index(ESODI) were analyzed by applying Monte Carlo simulation to the main feeder-line 4 of RBTS Bus-6. The overall reliability assessment of the urban microgrid was reported in[83].MATLAB programming has an extensive assortment of applications for analyzing the behavior of a power system with linear and nonlinear programming, reliability assessment, Simulink Parameter Estimation and Simulink Response Optimization. The models of DERs, microgrids, Lithium-ion batteries and solar PV systems were explained with the operational risks of a hybrid system were simulated in MATLAB/Simulink [84]. Based on the Reliability Block Diagram model, the reliability estimation of a microgrid system situated in Fermeuse, Newfoundland, and Canada were explained. The influence of stochastically changing wind speed was studied with MATLAB coding [85]. By using MATLAB, the reliability indices of a small autonomous hybrid power system were calculated [86].

ETAP power engineering software supports various electrical systems such as load flow, electric supply substation simulation, distribution system analysis and generation security, reliability calculation of renewable energy systems, wind and PV penetration studies. Reliability assessment of the electrical energy distribution system in Port Harcourt was presented using an analytical technique, and a comparison of the indices was made in ETAP software [87]. The reliability performance of the Bedele city power distribution system of the Ethiopian Electric Agency (EEA) of the existing distribution network with and without protection devices was presented by using ETAP software, and various faulty conditions of the system were summarized. [88]. Reliability assessment of the Dire Dawa city distribution system was undertaken, and the main causes of distribution interruption were identified by considering the past decade's data and primary interruption data. ETAP 16.00 software was used to carry out the simulation by varying the number of recloser circuit breakers [89]. The importance of the microgrid and its islanding conditions during the fault in the main grid in the ETAP environment were discussed [90]. Reliability assessment of Port Harcourt Town distribution system was undertaken by using the analytical method and ETAP software [91].

A practical case study of electrical load distribution system in Federal University of Petroleum Resources, Effurun(FUPRE), Warri were considered for reliability assessment . The substation constitutes of one Transformer with capacity of 2.5 MVA and six distribution substations i.e. 6 x 11/0.415 V outgoing transformers feeder for College of Science, Health Centre, Administration Block, College of Technology, Hostels and TETFUND Classroom Blocks. The system has a total number of 6,813 customers connected . By considering, historical data from August 2018 to August 2019 obtained from the Benin Electricity Distribution Company [BEDC] the analytical analyses were presented. The power distribution network has modelled and simulated using ETAP16.00. The reliability indices such as SAIFI, SAIDI, CAIDI and ASAI were calculated for all the substations and compared with IEEE Std.1366-2011. From the simulation results, it has been concluded that the Administration Block, Petroleum Lab has the maximum number of failure rates and Hostels, Tetfund Classroom Blocks had the highest length of outages. College of Technology was found to be the best reliable system in the FUPRE network. This type of reliability assessment helps the power operators in decision making regarding future load operations and periodical maintenances of substations[92]

DIgSILENT Power Factory, NEPLAN tool supports the analysis of the real-time simulation of a power system with several configurations, energy sources and system requirements. The simulation supports reliability assessment, performance monitoring and fault diagnosis. The reliability assessment of Distribution system RBTS – Bus 3 feeders 1 and 2 in NEPLAN version 5.5.1 and DIgSILENT Power Factory v14.0.511 were presented. The reliability indices were calculated by using the FMEA technique and compared with the simulation tool [93]. The reliability assessment of RBTS Bus 2 and Bus 4 with DIgSILENT Power Factory Tool was presented. A case study was undertaken for the reliability assessment of a 115 kV distribution system in the Chiang Mai region. The importance of installing protective devices for improvement of reliability was highlighted [94].

Table 1 : Summary of Reliability Assessment Methods

Methodology	Reliability Indices		Journals Referred	Indices
	HL- I, II	HL- III		
I. Deterministic Methods :				
Capacity reserve margin	✓		[23]	LOLP, Unserved energy
Probability Methods :				
Bayesian Network	✓		[24]	SAIFI, SAIDI, CAIDI, MAIFI, CTAIDI
Markov modelling & Frequency and duration concepts	✓		[25]	FOR, Failure and repair rates
Minimal cut sets	✓		[26]	Availability and unavailability
Fault Tree	✓		[27]	Failure rate, unavailability
Failure Modes and Effects Analysis		✓	[28],[29],[30],[31]	Failure rate, Annual outage duration, SAIFI,SAIDI,CAIDI, ASAI, ASUI, ECOST,ENS
Performance Analysis		✓	[32],[33],[34],[35], [36],[37],[38],[39], [40],[41], [42]	SAIDI,SAIFI,CAIDI,ASAI, ASUI, EENS, ECOST
Weibull and Exponential Distribution	✓		[43]	Failure rate and Frequency
II. Intelligent Methods :				
Credibility theory		✓	[44]	SAIFI,SAIDI,CAIDI,ASAI,EENS
Fuzzy Chance Constrained Programming		✓	[45], [46], [47]	SAIFI, SAIDI, CAIDI, ASAI, ENS, AENS
Artificial Neural Network	✓		[48]	SAIFI,SAIDI
Particle Swarm Optimization	✓		[49],[50],[51],[52], [53]	FOR, LOLE, EIR, DNS, EENS
Clustering	✓		[54]	FOR, LOLP, LOLE
Stochastic programming		✓	[55]	Energy indices
Stochastic mixed integer Programming	✓		[56], [57]	Safety and security indexes, availability, Mean time to failure, Mean time to repair
Genetic Algorithms	✓	✓	[58]	SAIDI, SAIFI, ASAI
Risk Analysis		✓	[59],[60],[61],[62], [63],[64],[65],[66], [67],[68],[69],[70]	SAIFI, SAIDI, ASAI, EENS
Nash-Cournot model		✓	[71]	Energy indices, Risk indices
Network reconfiguration		✓	[72], [73]	Failure rate, Annual outage duration, SAIFI, SAIDI,CAIDI, ASAI, ASUI
Disjoint Sum of Product		✓	[74]	SAIFI, SAIDI, CAIDI, ASAI
Power exchange algorithm		✓	[75]	Customer interruption cost, ENS
III. Simulation Tools :				
Monte Carlo simulation	✓	✓	[76],[77],[78],[79], [80],[81],[82], [83]	FOR, LOLP, LOLE,unavailability, SAIFI, SAIDI,CAIDI ,ASAI, ASUI , ENS, ECOST
MATLAB		✓	[84], [85], [86]	Reliability functions
ETAP		✓	[87],[88],[89],[90], [91],[92]	Failure rate, Mean time between failures, Mean time to repair, SAIFI, SAIDI, CAIDI, ASAI, ENS,ECOST
DIgSILENT, NEPLAN		✓	[93], [94]	SAIFI, CAIDI, ASAI, ASUI, ENS, ECOST

4 Summary

Reliability analysis can be helpful in various sectors of power systems to moderate the operational cost and energy cost and increase the reliability of a power system [95]-[110]. Table 1 summarizes the different reliability techniques based on the indices employed for analysis and supporting tools used. Figure 3 depicts the reliability indices obtained from various reliability assessment methods.

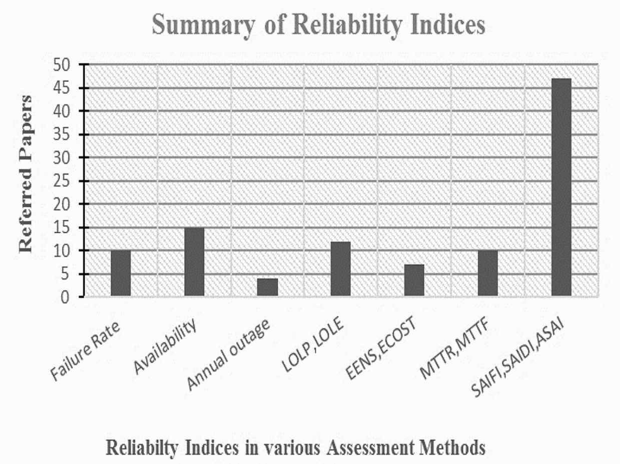

Figure 3: Summary of reliability indices in various assessment methods.

Based on a comprehensive literature survey on various reliability techniques, the following inferences are presented:

- The present review work has explored various reliability assessment methods in detail to reliably fulfil power system requirements. Most of the reviews emphasize historical assessment and analytical approach.
- Probabilistic methods such as Bayesian Networks, Markov modelling, Frequency and Duration concepts are mainly applied to analyze the system's availability and forced outage rate. Failure Modes and Effect Analysis, and Performance analysis are mainly used to ascertain the load point indices of the various practical distribution networks.
- From various reviews, it has been observed that the techniques such as particle swarm optimization, stochastic programming, fuzzy chance-constrained programming, and risk analysis are mainly adopted to face the challenges of power systems.
- It is evident that the reliability indices such as LOLP, LOLE, SAIFI, SAIDI, CAIDI, EENS and ECOST play a vital role in analyzing and evaluating the root cause of interruptions and supporting the maintenance of continuous power supply. The various reliability studies show that the commonly used reliability indices are SAIFI, SAIDI, CAIDI and EENS.
- Most of the reviews focused on simulation tools such as Monte Carlo, MATLAB and ETAP to attain satisfactory outcomes within the specified time for reliability studies.
- This kind of reliability evaluation will be helpful to power distribution system planners and operators for load forecasting and planning and expansion of the power system network in the future.
- It is also emphasized that the implementation of reliability assessment helps in devising optimal solutions for power quality issues and addressing the stability, operation and control concerns of integrated systems.

Reliability challenges in future Power systems

The future power system relies mostly on the renewable energy sources and its integration issues as DGs or as microgrids in the existing power sytem.Hence, there is a detaailed analysis, challenges and extensive research required addressing the issues of DG integration and microgrid operations with respect to the reliability. Further, the following research gaps has been identified:

- Integrated operations of Ditributed generation sources and energy storage systems with the distributed or decentralized control strategies considering active/reactive power sharing, power and energy management and various levels of protection with respect to reliability has to be analysed.
- Handling issues raised by renewable based generation considering uncertainty in respect to security and reliabilty perspective has to studied.
- Integration of new energy sources and Electrical Vehicles into existing system introduces complexity and interdependency problems and further leads to more challenging reliability analysis.
- Reliable operation of distributed resources with demand side management in the deregulated environment needs to be addressed.

5 Conclusion

This paper presents an overall review of reliability assessments techniques based on different aspects of reliability, reliability improvement methods with probabilistic, intelligent and simulation techniques. From this broad review work, it is evident that it is essential to consider reliability assessment as they can help reduce the interruptions of power supply that cause adverse effects on the distribution systems. This is valuable for power system operation and planning and provides the prospect to develop accessible preferences for an optimal approach. Thus, it is concluded that proper application of reliability assessment method sustains the power system to deliver quality and continuity of power supply to end-users and offers mutual profits to power companies and consumers.

Nomenclature

P_i Probability of a component being unavailable in the system.

t_i Number of times a component is unavailable during load operations.

DNS_i Demanded power not supplied at load point 'i'.

ENS_i Energy not supplied at load point 'i'.

t_j Period of time when the load exceeds the generation capacity

n Number of customers connected to load

r_i Average repair time of load point 'i'

N_i customers connected to load point 'i'

λ_i Failure rate

N_a Number of customers affected

U_i Annual unavailability

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