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# Power system reliability assessment - A review on analysis and evaluation methods

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**Abstract:** The structures of power systems and their capacity have been updated significantly from time to time. Therefore, a reliability analysis is an essential issue in the planning, designing, and operation of electric power systems. Thus, a number of methods have been proposed. These are grouped as analytical based methods, simulation-based methods, and hybrid methods. Some methods like Monte Carlo, Markov etc., developed and some indices such as interruption indices, energy-oriented indices, are used for the evaluation. The purpose of this review study is to investigate the reliability analysis approaches, methods and difficulties, and to report importance of the reliability analysis in power systems. Therefore, reliability indices and evaluation methods and models of evaluation of power system are listed and explained. Besides, modeling and computational burden and complexity and problems are discussed. The importance of reliability analysis for emerging power systems is examined and explained.

***Keywords:*** *Emerging power systems, Reliability analysis, Reliability indices*

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## 1. INTRODUCTION

Engineers working on power systems have always been dealt with providing reliable energy to the users. Reliable power systems are defined as systems that can provide energy with quality and characteristics in the relevant standards. In general, the energy produced in power plants flows through a traditional centralized controlled transmission and distribution system to the customers as in Fig. 1. Thus, any failure or any incident in any of these parts, in any operation and in the traditional power system control may affect a lot of users, and assets [1]. Many of blackouts and brownouts are happening because of slowness on mechanical switches, non-automated parts and being unaware of the failure status. In contrast with that, the distributed generation resource management and the decentralized control can help to reduce these impacts with high redundancy and the enhanced control ability on generated and consumed electrical energy within the power system [1,2].

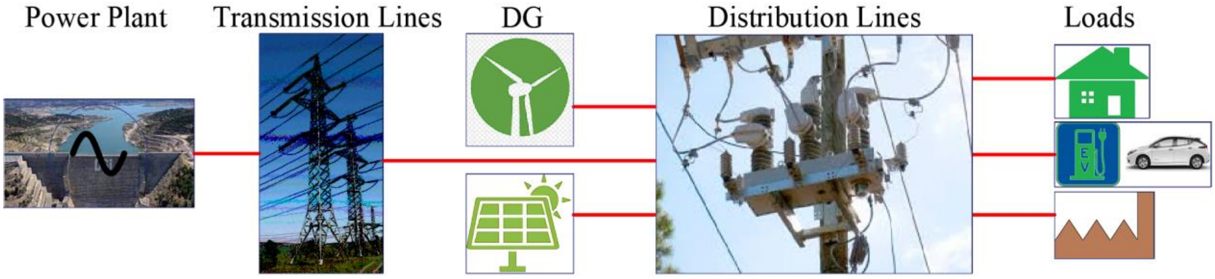


*Figure 1. Power flow structure in a conventional power system.*

Today's power systems are elevated with enhanced communication technologies and control systems. Besides, increasing renewable energy integration whose energy generation capacity is depending on natural effects and may be intermitted also brings some uncertainties. These uncertainties also cause some disturbances on the energy quality and the power system reliability (PSR) [3,4,5,6]. If proper design and analysis studies are not performed, the power system with renewable energy penetration may cause non-effective use of renewable resources and possible failures in power systems [7,8]. Therefore, developing new methods and models for evaluating and enhancing PSR is necessary [3]. Traditional power systems' infrastructure operations require less complexity, less difficulties and higher efficiencies to maintain the future system demand [3]. Especially the distributed generation, which has been growing increasingly on today's electricity network, leads to power quality problems. This kind of generation reveals stress on system when integrated with conventional grid and bidirectional power flow. Because of these efforts, adequate reliability level for power systems is required [4].

PSR has become a very important concern while the electricity demands are increasing and it pushes boundaries [1]. Providing continuous electrical energy to the customers at the possible lowest price and desirable service quality are the necessary for electric power utilities [9]. A distribution system's quality of service ensures economically effective investment and mitigates reliability risk of consumers [10]. The distribution system can be evaluated by its reliability indices and this reliability can be improved with the automation of distributions feeder and related parts. Hereby, desired decrease in power interruptions would occur [3].

The evaluation of the electric PSR is a constituent part of operation and planning of both traditional and current power systems [11]. Evaluation of the PSR is more crucial nowadays due to today's randomly changing power system behaviors because of the penetration of disturbed energy sources such as PV, wind energy and electric vehicle (EV). More accurate PSR evaluation techniques are needed in order to handle changes in system such as aging of electrical devices in the system [12]. Thus, the power systems equipment is also particularly concerned with their failure indices [13]. Each electrical equipment should be coherent with its existing period. The equipment life is splitted in to three periods. These are infant mortality, useful life, and wear out periods. Of these, "useful life period" is the one, which is generally used in traditional reliability evaluation. An equipment up (time to failure) and down (time to repair) times are evaluated to be exponentially distributed [11]. Another concept, which should be considered in PSR evaluation related to the equipment lifetime, is divided three stage as physical expected lifetime, technical expected lifetime and economic expected lifetime [14]. Specifying lifetime of the component is a challenge for reliability perspective and requires category of evaluations called Reliability-Centered Maintenance (RCM). RCM implementation is a step for “getting the most out” of the installed equipment. Because this implementation needs long time to collect required data, various mathematical models have been proposed [15].

Modeling renewal process of an equipment is another part of the PSR evaluation. Decreased reliability because of current equipment’s age decreases power utilities value and also requires large amount operations and repair costs [14,16]. Replacing aged equipment completely in infrastructure is not feasible method. Using cyber technology in infrastructure help to equip via required information for fast incident detection and diagnosis, and so grid is able to prevent propagation of failure. In smart grid which is enhanced power grid, the reliability more increased than traditional grid naturally thanks to fast communication and intelligent control capabilities [17].

Many studies have been focused on PSR analysis. Some of these studies are presented between 1960 and 2000 [18-23]. Electric Power Research Institute’s (EPRI) white paper combined distribution system reliability related publications including principals, concepts and regulations in 2000 [24]. In [25], reliability analysis indices and their use on system planning are explained. Transmission and distribution reliability evaluation are also discussed. In [26], PSR assessment techniques are introduced with various methods. In [27], computational techniques are introduced for PSR evaluation. In [28], reliability studies, later than 2000s, on power systems including current challenges, recommendations and new research directions are investigated. In [29], research on PSR investigated before and after 2000s, and the PSR research framework is presented. In [30], PSR criteria performance evaluation framework is presented.

As it is seen above, although some review papers have been published on reliability analysis of power systems, these studies are generally old. Because of the technical improvements, increasing concern on energy price and continuity, and increasing risk in parallel to the increasing penetration of renewable energy resources and distributed generation systems, the power system by itself and concepts, methods and devices used in power system are changing fast. Along with the power system, reliability analysis concept and its components are changing. Therefore, this study is performed to highlight the recent discussions on reliability analysis of the power systems along with the general descriptions and discussions. The purpose of this review is to investigate PSR analysis approaches, methods and difficulties, and to report importance of the reliability analysis in power systems. Power systems are classified according to the reliability assessment. Challenges on power systems reliability is also presented, and reliability necessities on power system are discussed. Besides, PSR indices for analysis and reliability methods for evaluation are explained.

## 2. SYSTEM CLASSIFICATION

Although, making a complete classification and categorization is not possible for all type of PSR evaluation, some basic definitions can be described as following [31].

- *Reliability evaluation of the large power system: In general, a bulk power system can be described large, because it includes hundreds or thousands of buses and lines. Thus, modeling this kind of big systems are required high level details. Reliability indices of some physical components are required to compute with high accuracy. Since large power systems reliability evaluation is more challenging, generally comparisons are made with other alternative plans.*
- *Transfer capability studies: In these studies, power transmission system sufficiency is examined.*

- *Interconnected systems studies: In these studies, interconnection sufficiency between another systems or utilities is evaluated for economic aspects and emergency situations. These systems are generally simplified and assessed with corresponding grid, sources and loads.*
- *Area supply system reliability: These studies are related to small-scale power systems like as local supply grids and power stations. Local power station equipment basically circuit breakers have very important role. Non-continuity between supply and load spots are used for the system failure evaluation. Like just previous classification, generally alternative networks are compared.*
- *Economic studies: This topic is interested with costs which are changed because of changes is network and load configuration and other scenarios. Calculation results are important for required energy sales and predict sales potential. The evaluation is also important for any delay on commissioning [31].*

## 3. PROBLEMS COVERED IN RELIABILITY ANALYSIS

Unlike one-way power flow configurations (one-way power flow from large plants to loads), there are new conditions in electrical industry due to deregulations. Previously, customers did not contribute to the grid due to traditional one-way power generation. Thus, the electric power system is to provide electrical energy with acceptable quality, lowest cost, optimum reliability and easy to control. The PSR is segmented to a lot of components and subjects. Providing optimum reliability is the major subject, and an attention must be paid during the power system planning and operation phases. Electric power grid, nowadays, is changing remarkably with its regulations, structures and operations. Therefore, the reliability is more crucial and so new reliability methods, algorithms and software are widely used and required more than traditional system [32,33].

User cost and its reliability of the power system have inverse correlation. Fig. 2 shows the correlation between total system investment cost at operation and planning phases and reliability level. If the investment cost is increased, the reliability level can be increased as well. Failures related to user cost decrease when the reliability increases. Sum of these two costs give the total life cycle cost. The minimum level of the total life cycle cost is the optimum point [28]. Thus, catching the balance between investment and reliability level is the main challenge at planning and operational phases of power system. The purpose is to provide continuous and quality electrical power to the customers and keeping the cost at minimum at the same time. The balance point is adjusted according to regulation standards and customer needs [28,34].

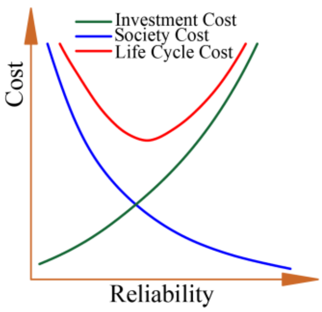


*Figure 2. The correlation graph between reliability index and total system investment cost.*

There are several difficulties in this area:

- *Conceptual - difficulties related to specifying the aim and purpose of reliability assessments, and choosing the proper indices and failure criteria clearly.*
- *Modeling - difficulties related to using right mathematical model according to failure, repairment, load, weather condition and generation schedule.*
- *Computational - difficulties related to specifying the most accurate solution methods with acceptable computational efficiency.*

- *Data Collecting - difficulties when data is not available and is not sufficient [31].*

The aim of the PSR is considering all related factors in accurate and optimal computational effort [31]. The failure and repair process is a complicated concept. Even if utilities have their outage data, fewness of outages cause uncertain results. To overcome this issue, similar component data are evaluated together in order to evaluate the reliability more accurately. Classifying issues which have similar effect on the system is a practical and generally uses reliability modeling technique [31].

Power systems may have a large number of equipment and their failures are stochastic. For reliability evaluation of this system, in theory, all possible combinations of equipment failures must be considered. If a system has *n* independent equipment, totally $2^n$ incidents should have to be considered. If this system includes hundreds or thousands of components, the reliability evaluation may not be possible. Therefore, the approximation method has been proposed. This method provides adequate level accuracy without evaluating all possible indices [31].

PSR concept can be expressed with following three categories [34,35]:

Adequacy, is the system ability to supply sufficient demand power regarding the scheduled and expected unscheduled outages. Security, is the ability to handle any kind of disturbances (e.g. short circuit). Quality, is ensuring specific voltage and harmonic levels.

PSR problems can be expressed as following [32,36]:

- *Continuity of the current system reliability level.*
- *Determining the most cost-effective investment projects for continuity of system reliability.*
- *Specifying and generating required reliability metrics for power system planning.*
- *Ensuring the compatibility of predicted reliability assessments and future system parameters.*
- *Assessing the reliability regarding to the failure cost.*

The reliability definition may include different perspectives. The customer perspective and the utility perspective are two main perspectives of a power system [1]. Customer Perspective is the quality of service availability of appliances. It depends on customers' end-use patterns [37]. Appliances must be usable during a day with required service quality. Thus, any service interruption is not acceptable from customer point. Utility Perspective is reliability of service at demand side and reliability of the supply side at customer load points. It is related to equipment availability: the generation, the transmission and the distribution assets reliability. Service reliability and reliability at load points that consists of the generation, transmission and distribution components are related to utility perspective [1]. Fig. 3 depicts the summary of reliability perspectives [1]. While evaluating the PSR in terms of interruptions, the frequency of the interruptions, the duration of the interruptions and severity or extent of the interruption should be considered. While first two considerations are important for both utility and customer, the last consideration depicts the number of affected customers [1].

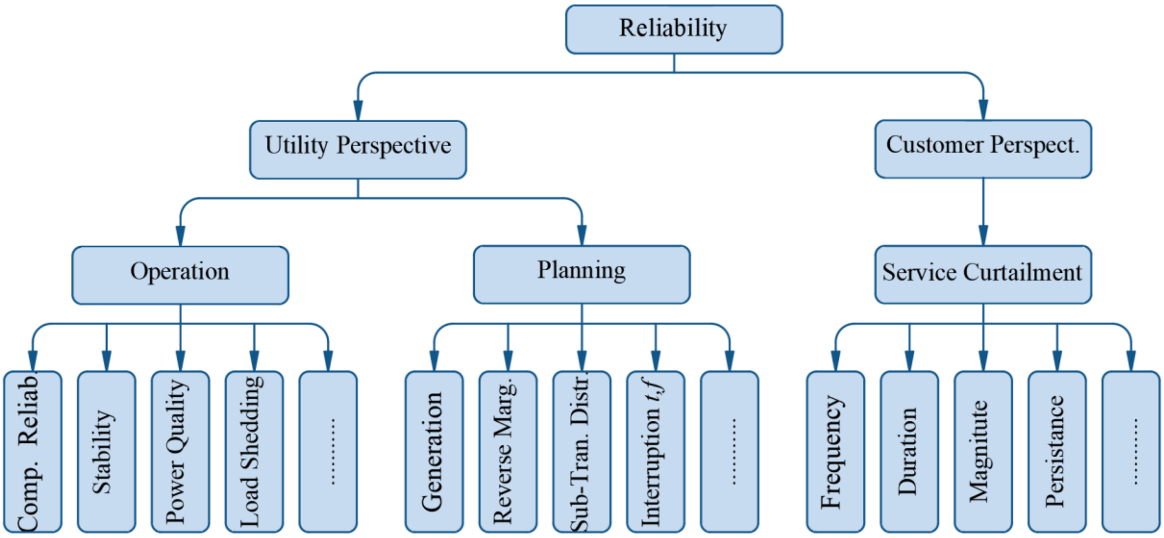


*Figure 3. Reliability concept from different perspectives.*

## 4. RELIABILITY ANALYSIS APPROACHES

Energy service reliability, energy efficiency and renewable energy such as wind, PV are types of research focus in the power system domain. The energy efficiency provides smart energy saving systems. Renewable energy supplying provides smart grids advancements. Service reliability provides PSR [29].

In power system service reliability researches, possible use cases can be categorized into four topics: regional, subcontinental, feeder, and local distribution system. Renewable energy can also be described with their use cases regarding to their effect on reliability of the grid. Since energy generation and new developments on the PSR is the rising concern and it has various research topics [29]. Fig. 4 shows a framework for PSR.

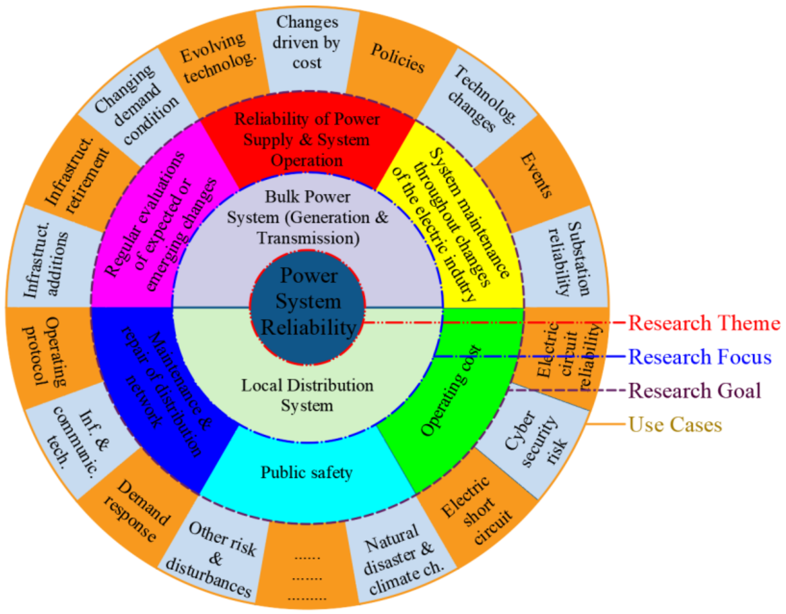


*Figure 4. PSR research framework.*

PSR and safety is basically constituted to two aspects: "the safety and reliability of power grid" and "the safety of communication information" as given in Table 1 [38]:

*Table 1. Safety and reliability indicators (from [38]).*

| Aspects | Indicators |
|---|---|
| Power grid safety and reliability | Amount of power transmission accident |
| | Amount of power transformation accident |
| | The self-healing speed of the energy distribution system |
| | The self-healing rate of the energy distribution system |
| | Urban user power source reliability |
| | Rural user power source reliability |
| The safety of communication information in power system | Safe activity data and communication index |
| | Amount of data of events |

Power system efficiency and economy are important for the network operation and transmission cost reduction and using energy resources and components efficiently. Economy and efficiency index of power system can be divided into three categories as economical advantages, network efficiency and staff productivity, which is given in Table 2 [38]:

*Table 2. Economics and efficiency indicators (from [38]).*

| | |
|---|---|
| Economic benefits | Value-added services revenue |
| | Electricity recovery |
| | The fair electricity consumption coefficient |
| Grid efficiency | Yearly maximum load level utilization |
| | Yearly maximum power lines load level rate |
| | Yearly average equivalent line operation load rate |
| | Yearly maximum load main transformer rate |
| | Yearly average correspondent load main transformer activity rate |
| Staff efficiency | Transmission worker performance |
| | Transformation staff efficiency |
| | Urban distribution network staff efficiency |
| | Overall labor productivity |

Various tasks can be evaluated by power system planner [31]:

- *Reliability trends specification*
- *Various system plan comparison*
- *Reliability metrics and design development.*
- *Power system performance evaluation regarding to reliability metrics*
- *Choosing proper bus schemes*
- *Specifying weak points of system*

For useful probabilistic reliability study, following topics should be met [31]:

- *The study must match the system size.*
- *The system model must have exact precision as much as possible for the aim of study.*
- *The computation results must be as precise as possible within predefined boundaries.*
- *The computation speed must be as fast as possible while running at acceptable time.*

The PSR analysis is generally categorized into three parts in order to specify boundaries of the reliability evaluation. It is called hierarchical levels, and that could be express as given in Fig. 5 [26]:

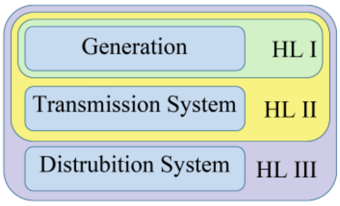


*Figure 5. Power system hierarchical levels*

Hierarchical Level-I (HL-I) contains simply producing and load of the power system. A PSR study of HL I is an evaluation of the all system generating power level which is required to satisfy the anticipated system requisition [26]. The forecasting is important to ensure the resource allocation of generation capacity for future needs of customers. Thus, predicted reliability indices are the fundamentals of evaluation of expected system load including both customer demand and grid losses and for the performance of future generating units [32]. The historical criteria of deterministic evaluation of the power system is now generally replaced by probabilistic criteria. The achievement of the probabilistic criteria can be obtained with various indices. Widely used PSR indices at HL 1 are: Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Expected Energy Not Supplied/Loss of Energy Expectation/Expected Unserved Energy (EENS/LOEE/EUE), Energy Index of Reliability (EIR) [32].

In the PSR field, Hierarchical Level-II (HL-II) is often defined as the “bulk power system”, involved generation and transmission stages. Therefore, a reliability study of the HL-II commentates the power generation capacity and transmission capacity to provide the system load requirement (bulk load points) [26]. Power network reliability is specified by level of task executions. These tasks are: necessary power delivery and sufficient energy quality; providing to the grid; power out of the stations; power exchange between connected network utilization [32]. PSR evaluation and analysis methods can be categorized into two groups: analytical and simulation. Analytical models are using reliability indices calculations which consist of related mathematical models. Unpredictable events are the problem of the assumption. Thus, when using analytical approaches, generally, adequacy of power system is estimated. [32].

Hierarchical level-III (HL-III) includes all power structure (including generation level, transmission level and distribution level). Because of the scale and complexity of the power system, the reliability study of the HL-III is characteristically only practically applicable for small scale power systems [26].

As a remedy in these systems is to use the results from an HL-II evaluation as an input for a separate evaluation of a particular distribution system. In this structure, the effects of the distribution system on the reliability of transmission and generation systems are ignored [26].

Generating unit status can be turned to several possible states as shown in Fig. 6. When a network element is made out of service intentionally, it is called planned outage. Here, the reason is generally repairment of a component and/or a planned maintenance. If an unpredicted outage occurs or if there is an outage due to any emergency condition that is called forced outage [25].

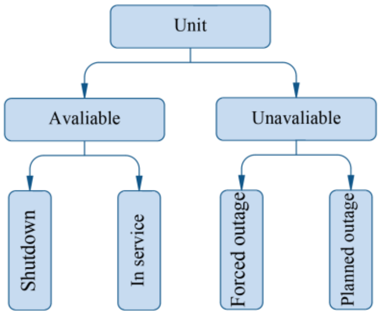

*Figure 6. Possible states of generation units [25].*

### 4.1. Aim and Use of PSR Studies in Operations

The PSR is not only a concern for planner, it is also important for an operator. However, the reliability term is different for these two. Using or applying reliability methods to the system is also different for these two. For instance, an operator evaluates the reliability for system operating states. A planner evaluates the reliability for design state with all possible states. While operators deal with short term risk evaluation, planners deal with long term assumptions. Operators need to decide faster and these decisions need to have minimum delay. The aim of the operation reliability evaluation generally is to assist in setting and execute different operation policies, so, serious sudden system failures can be anticipated. These must be executed to keep operation risks at acceptable level and uniform, to balance the cost and reliability, to decrease effects of disturbances and to minimize catastrophic failures [31].

Reliability studies are divided into three main categories of purposes: The first category is the Long-Term Evaluation and examines the current and future reliability of power system in the areas of generation, transmission and distribution. It provides long term perspective and demand-side resources. This assessment helps to the industry, regulators and policy makers to develop their strategies. The second one is Medium-Term Evaluation, and it examines the grid reliability for medium-term planning. It refers to few-days. It assists more standing solutions to short-terms contingencies. The last one is Short-Term Evaluation and it is performed to assist day to day operating decisions. The aim is to select ratings, locations, maintain distributed energy sources integrity to operate within its long-term ratings all the time and reduce the distribution energy loses [37].

According to their evaluation times, various actions need to be performed for reliability perspectives. These categories and actions are listed below in detail [31]:

Time Frame-A (short-term)

- *Available generation capacity cost utilization.*
- *Sufficient spinning reserve to decrease of system failure risks below the specified level.*
- *To increase economical operations and mitigate the emergency, evaluate the power amount that could be sold or can be buy.*
- *Selecting right actions for possible incidents.*

Time Frame-B (medium-term)

- *Lack of hydro-power energy.*
- *Effect of the stochastic nature of hydraulic energy.*
- *Scheduling of energy costs.*
- *Evaluation of transmission transfer abilities.*
- *Evaluation of requests for deviations from dedicated plan.*
- *Component maintenance and revision planning.*

Time Frame-C (long-term)

- *Storing and get units back into service.*
- *Fuel purchase agreements.*
- *Long time interval energy costs.*
- *Evaluation and revision of the operation policy.*

It can be seen that time frame-A basically helps to operator to be able to make a decision. Time frame-B is basically for setting operating policies. As some European utilities practice (eg., ENEL), assessments in time frame-B and C are executed yearly in order to assure to make constant risk over the years [31].

The reliability is one of the measuring indexes of distribution network. There are two basic parameters to evaluate reliability: *load point indices* and *system reliability indices*. These parameters are used in the calculations so gives mathematical results of demand satisfaction [37].

**Load Point Indices:** They include the load point failure rate, the average outage time and the average annual unavailability or outage. Values are computed through some techniques such as Markov Analysis Technique and Fault Three Analysis Technique. The stochastic nature of a distribution system behavior makes the indices, used to evaluate the system reliability, to be determined on annual basis by choosing random values. They are functions of the distribution system component failure rates, repair times and restoration times within the year. The average values are computed through associated analytical techniques such as Markov Analysis and Fault Tree analysis. The load point indices include the load point failure rate, the average outage time and average annual unavailability or outage. The load point indices are very important for customer viewpoint [37].

**System Reliability Indices:** It is very important for the system performance and reflects the sufficiency of the whole distribution system to indicate the system behavior. It can be divided into two categories: *Interruption Indices* and *Energy-Oriented Indices* [37].

### 4.2. Interruption Indices

Interruption indices are used to evaluate the average number of sustained interruptions noticed by a customer for long-term sustained interruptions. Based on the IEEE Standard 13666-2012, the basic indices used are System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI) and Average Service Availability Index (ASAI). The SAIDI is considered the most common one to evaluate the system performance by calculating the sustained interruption of each customer in service area during determined period (minutes or hours) per year. The SAIFI is used to indicate the average number of interruptions happened to a customer within one year. The improvement of SAIFI's index level of the distribution system is the main goal to reduce the number of sustained interruptions that occur in the power grid. Decreasing the CAIDI index has the tendency to decrease the number of customers' complaints. The CAIDI's outage duration is one year. The ASAI's available service period is mostly monthly or yearly [37].

$$SAIFI = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customer Served}} = \frac{\sum_i \lambda_i N_i}{\sum_i N_i} \tag{1}$$

$$SAIDI = \frac{\text{Sum of Customer Interruption Durations}}{\textit{Total}\text{ Number of Customer Served}} = \frac{\sum_i U_i N_i}{\sum_i N_i} \tag{2}$$

$$CAIDI = \frac{\text{Sum of Customer Interrruption Durations}}{\text{Total Number of Customer Interruptions}} = \frac{\sum_i U_i N_i}{\sum_i \lambda_i N_i} \tag{3}$$

$$ASAI = \frac{\text{Customer Hours of Available Service}}{\text{Customer Hours Demanded}} = \frac{\sum_i N_i \text{x} 8760 - \sum_i U_i N_i}{\sum_i N_i \text{x} T_h} \tag{4}$$

where $N_i$ is the number of served customers of $LP_i$ (Load Point), $\lambda$ is the interruptions, $U_i$ is the duration, $T_h$ is the total hours that is *8760* for one year [39].

### 4.3. Energy Oriented Indices

These indices are very important to evaluate the load in distribution networks.

#### 4.3.1. Energy Not Supplied Index

Energy Not Supplied Index (ENS) is used to calculate the total energy generated but not supplied by the system:

$$ENS = \sum L_{a(i)} U_i \tag{5}$$

where $L_a$ is the load at location *i*, $U_i$ is the duration of the outage [37].

### 4.3.2. Loss of Load Probability Index

LOLP is a stochastic method. It is used for specifying of reserve needs. It was introduced at 1947. This approach analyses possibilities of simultaneous outages of generating elements, specifies expected capacity shortages in number of days for every year together with daily peak hour loads. LOLP is currently widely used approach by utilities for the assessment of the generation capacity requirement [40].

When a generation component is lost, it causes the awaited risk of losing power supply $E(t)$ and this expectation can be specified as mathematical formula as following [40]:

$$E_i(t) = p_i t_i \tag{6}$$

where $p_i$ is the probability of loss of capacity, and $t_i$ is the duration of loss of capacity in percent. When LOLP is calculated for the whole system level, it is specified as total of all mathematical definition for every component [40]:

$$LOLP = \sum_{i=1}^{n} p_i t_i \tag{7}$$

Yearly evaluations of LOLP are carried out in four steps:

- *Yearly maintenance calculations of generation units and making a schedule.*
- *Creating capacity outage table for specific weeks.*
- *Calculating daily outages and summing days for weekly trend.*
- *Calculations can be done again for every week in a year.*

LOLP ideal reliability level calculation is based on historical data. The procedure includes following four steps [40]:

- *Specify utility expenses.*
- *Specify ideal economical actions for energy customers.*
- *Calculate the all cost as the sum of first 2 steps.*
- *Obtain minimum cost by repeating first three steps.*

Sum of the utility and customer cost is the total cost [40].

### 4.3.3. Loss of Load Expectation Index

LOLE can be calculated from daily peak load change data (shown in Fig. 7). A specific outage of capacity assists the system with number of stochastic outages existence and number of time units. The calculation period can get weekly, monthly or yearly. The easiest way is using yearly data for calculation. If the daily peak load data is used on annual basis, LOLE is in days per year. Following equation shows LOLE calculation [40].

$$LOLE = \sum_{i=1}^{n} p_i t_i \tag{8}$$

In equation, $p_i$ is the solely probability of capacity during power outage and $t_i$ is time interval of loss of power source as days.

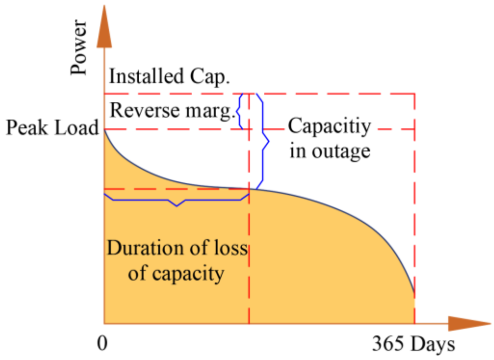


*Figure 7. Load curve in yearly.*

If the cumulative LOLE probability $P_i$ is used, the required equation is given below [40]:

$$LOLE = \sum_{i}^{n} P_i(t_i - t_{i-1}) \tag{9}$$

LOLE can also express with a probability that consumption $L$ will not be enveloped throughout employed power capacity $C$ [40].

$$LOLE = \sum_{i}^{n} P_i(C_i - L_{i-1}) \tag{10}$$

The fundamental of LOLE approach is very flexible. Following three steps show the way to LOLE calculation which can be used to specify yearly risk index [40]:

- *Taking into account the maintenance requirements on a monthly basis.*
- *Taking into account the neglected maintenance requirements.*
- *Worst period basis.*

Conventional LOLE is used for specifying the required installed capacity, regarding to the expected peak periods capacity. In order to specify power capacity amount for a single power plant both LOLE and LOLP indices are necessary. After the power capacity calculation, the desired reliability goal can be achieved [41].

### 4.3.4 Energy Index of Reliability

The area under the load duration curve shows the generated energy at certain time span. It can be used for calculation expected energy not supplied due to inadequate installed. Proportion between energy shorten due to decreased capacity due to the certain capacity in power outage and the all energy generated can be called as energy index of unreliability. EIR is complementary function of the LOEE and it can be described as its complement as below [40].

$$EIR = 1 - LOEE\% \tag{11}$$

### 4.3.5 Loss of Energy Expectation Index

Generation capacity exceeding outages cause reduction on system load energy (Fig. 8). The possible energy reduction is got as a multiplication of a possibility of amplitude of certain capacity in power outage and the energy reducted by a certain capacity in power outage. Total of them presents the LOEE as in (12) [40]:

$$LOEE = \sum_{i=1}^{n} P_i E_i \tag{12}$$

In equation, $P_i$ refers to the probability of amplitude of certain capacity in the power outage, $E_i$ refers to energy curtailed by a specific capacity in the power outage, and $E$ is the total energy under the load time span curve.

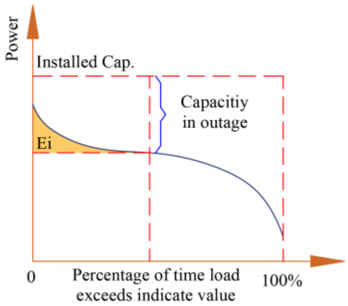


*Figure 8. Energy reduction by a given capacity in outage or loss of energy expectation.*

Normalized LOEE (LOEE% or LOEEp.u.) is got by evaluating the total energy under the load time span graph. Normalized loss of energy prospect equals to energy index of unreliability [40]:

$$LOEE = \sum_{i=1}^{n} \frac{P_i E_i}{E} \tag{13}$$

## 5. RELIABILITY ANALYSIS METHODS

Reliability evaluation methods for distribution networks have two major methods: *Historical Assessment methods (HAM)* and *Predictive Assessment methods (PAM)*. The HAM focuses on the gathering and analysis of distribution system power outage and customer discontinuance data. Electric utilities use HAM rather than PAM to measure effective distribution system reliability performance levels and obtained performance indicators to provide reliable power supply and cost effectiveness to all electric utility customers. Predictive reliability assessment involves both *historical component outage* data and *mathematical* models. This method is typically used to estimate the overall performance of particular configuration. Predictive methods can be divided into two main categories: *simulation* and *analytical* methods [37].

### 5.1. Simulation Methods

Simulation methods are designed to investigate large and complex systems and to provide numerical solution in order to overcome limitations of analytical solutions. The most common simulation methods in distribution network component reliability assessment are *Structure Function* and *Monte Carlo Function*.

#### 5.1.1. The Structure Function

It is computed to locate the state of the system. It is a Boolean structure that is used to identify a specific output of the distribution network components. Additional structure functions can be used to match all the system possible status at the cost of increasing the complexity of the analysis [37]. When a system functions consist if and else if all components function, the logical structure is a series structure as in Fig. 9:

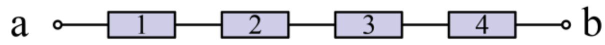

*Figure 9. A series logical structure.*

When a system functions if at least one of all possible *n* components functions, the logical structure is a parallel structure, as depicted in Fig. 10. Series and parallel structures can be further combined to model more complex structures [42].

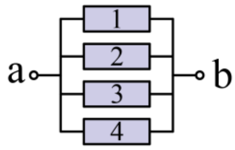

*Figure 10. A parallel logical structure.*

### 5.1.2. Monte Carlo Function/Simulation

Monte Carlo Function, also known as Monte Carlo Simulation (MCS), produces random failures from every unit's failure data. MCS depends on replication of the process of power system in a certain time. It is a powerful, flexible tool for risk analysis, and it shows better solution for practical system behavior. It brings various output parameters such as probability density functions and their respective moments [37,43]. MCS can be carried out numerically or analytically. Since computer technology was emerged, numerical simulation tools have become easier to use. Numerical tools are commonly performed for power system performance calculation. Simulation process gives advantage on estimation of a certain performance calculation with given system data. When the system data variation is vast, the simulation output sensitivity can be increased with repeated simulations. Another benefit of this simulation is that it can evaluate alternative system designs and can show optimal design. MCS can be used on large and complex systems. MCS can be used when analytical calculation methods cannot be applied due to complexity. MCS is performed with large number of samplings when higher accuracy is needed [44]. This estimation of large sample sizes is required for low error probabilities. This is the main problem with MCS. The Modified Monte-Carlo Simulation (MMCS) reduces the required sample sizes [45], [46]. Thus, MMCS method can enhance the computational efficiency greatly [47].

### 5.1.3. Modified Monte Carlo Simulation (MMCS) Method

Traditional MCS can evaluate the usability of radial and open-ring networks when modifications are required to be proper for reliability evaluation of closed-ring networks. There is an example flowchart of Total Loss of Continuity (TLOC) description in MCS to evaluate and analyze the reliability of closed-ring network that is named MMCS method [39]. Here, time-to-failure (TTF) and time-to-repair (TTR), given below, becomes important parameters in evaluation:

$$TTF = -\frac{1}{\lambda}\ln(r_n) \tag{14}$$

$$TTR = -\frac{1}{\mu}\ln(r_n) \tag{15}$$

where $r_n$: a random number, $\lambda$ is failure rate, $\mu$ is repair rate, and *PLOC* is partial loss of continuity [39].

## 5.2. Analytical Reliability Analysis Methods

The analytical reliability method indices have some advantages over the simulation method such as being used with any normative application, giving the same numerical result for the same system, same model and same input data set. The simulation method result is dependent on modelling capability and the number of equipment used in simulation which extends the simulation time and needs expensive computational hardware. The analytical approach model is often a simplification of the system, while, in the simulation approach, it simulates any characteristics that can be recognized. The solution time is relatively short for analytical techniques comparing to the simulation techniques. The disadvantage of these methods is high solution time for the applications that requires several reliability assessments [37].

#### 5.2.1. Network Modeling

Network Modeling depends on the solution of logic networks. The network reliability analysis and modeling have developed widely over decades [48]. The main concern on network design is to manage component failures effectively. The first concern is effective management of connectivity. Performance problems occur more widely in real environments. However, the connectivity problems are more catastrophic as they occur less frequently. The network reliability was first concerned for connectivity issues [49]. It is the most popular technique for distribution system reliability analysis due to the simplicity of the method and natural similarities between network model and distribution topology [37].

#### 5.2.2. Markov Modeling (on Distributed Generation)

When Distributed Generation (DG) components are lack of their available capacity, failures occur to restore the supply. Since DG components are naturally stochastic, so probabilistic reliability evaluation models are used. Various Markov Models can be performed. This model is described by up and down states and transitions between them. The other option consists of degraded states in this model which shows various level of distributed power generation as shown in Fig. 11. In the Markov Model, when there is dispatchable generation, the power from generation of every states is known and stable. In contrast, when the generation is from non-dispatchable DG like solar and wind, it is evaluated by the available variable resources and need to be specified. The sufficiency of Markov Model is entailed regarding to chosen technique and DG operating mode [50].

Markov Modeling is used for analysis of system reliability, availability and maintainability. A system consists of number of units and they are running or in failure state at any given time. The whole system's successful operation depends on its units' failure or success times. Thus, system can stay at one of two states [50]:

- *Operating state, where the system is working even if it consists of one or more failure units. When all system units are working successfully then it is called fully operational system.*
- *Failed state, where the system is not working due to one or more failure units.*

This kind of model ensures obvious representation of all system states and transition between them [17]. This model is also used for power system units, individually. However, its main disadvantage is difficulty of the creating a diagram for a large power system consisting of many units. When the number of existing units, *n*, existing number of states is equal to $2^n$ [40].

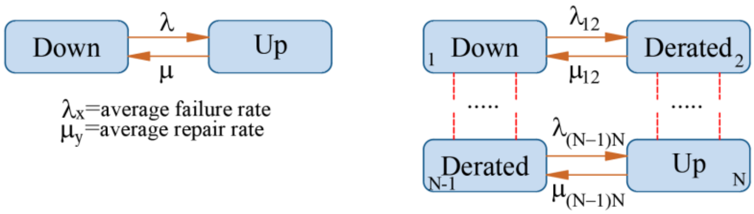


*Figure 11. Two states Markov model (left) and example of N-states with derated states (right).*

#### 5.2.3. Fault Tree Analysis

The fault tree is a graphical model that evaluates wide range parallel and sequential combinations of faults according to the occurrence of specified unwanted event or top event. The fault tree model uses logical gates for reliability evaluation. Fault tree's logical gates implement the primary event to the top event. Primary events are not developed further. Basic events and house events are example to primary event. Basic events are the most important part of a fault tree. They symbolize undesired events with their failure state. The component failures, the missed actuation signals, the human errors, the unavailability because of the test and maintenance activities, the common cause failure (CCF) contributions, and software errors are example of the basic event. The house event shows true or false conditions. It is a connection between the gates and the basic events [40].

Failures are certain events that are results of the failure states. They are directly linked with failure reasons of the units. If a relay cannot close due to broken contacts, this failure belongs to the relay. However, if the relay cannot close due to signal does not reach to the relay, this failure does not belong to the relay. Even if this is not the relay failure, the relay cannot operate successfully as expected, this is considered the relay fault in this case. The fault tree is not a whole equipment fault model. It is related only faults or failure modes that may cause the top event. Even if the fault tree is a static tool, it can also be used for semi-dynamic or dynamic attempts by changing [40].

### 5.2.4. Event Tree Analysis Method

Event tree analysis method is used to identify possible accident sequences related to a specific primer events. The event tree model specifies the logical connection between the possible success and specified safety system or function failures when they act to primer and sequential events. These sequences show safety system's available success and failure actions in the evaluated system. These sequences consist of primary event and the safety function failures and the successes. The event tree is a standard reliability evaluation tool in stochastic risk evaluation, and it acts the safety system responses which is following the primary event [40]. Fig. 12 shows the event tree model development process:

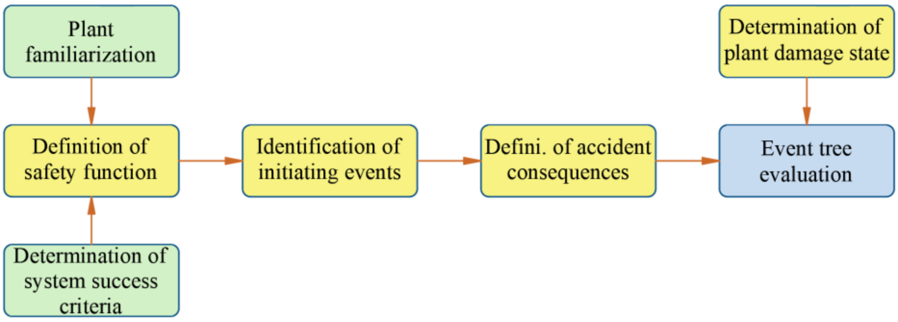


*Figure 12. Event tree development model process.*

### 5.2.5. Common Cause Failures

CCF case are a subtitle of subsidiary cases that fault states of two or more components are present simultaneously and are an exact result of a shared root cause. CCF is related to dependent failure. The events A and B are dependent if [40]:

$$P(A \cap B) \neq P(A) \times P(B) \tag{16}$$

In equation, *P(x)* refers to the probability of case *x*. If there is an interdependent between parallel cases, the system malfunction possibility is bigger than product failure possibility of whole parallel cases [40]:

$$P(A \cap B) > P(A) \times P(B) \tag{17}$$

Two fundamental factor's co-occurrence result CCFs: (i) unit sensitivity of failure or unavailable due to a specific reason of failure and (ii) a coupling system which makes the situation for multiple units to be effected by the same cause. An example can be given with two parallel relief: two parallel relief's valves fail because cannot be opened at the specific pressure because valve opening value is set to higher value than it should be. Therefore, with this incorrect set, two valves fail together. Fig. 13 depicts common dependent event elements [40]. CCF analysis procedure is generally categorized in two fundamental phases: Phase I- Identification phase and Phase II - Evaluation phase. The identification phase is to identify unit groups in the system whose CCF contributes to the system failure possibility or to the system unavailability importantly. The evaluation phase is for choosing suitable method of CCF, gathering adequate parameter data for analysis and carrying out qualitative and quantitative analysis of CCF [40].

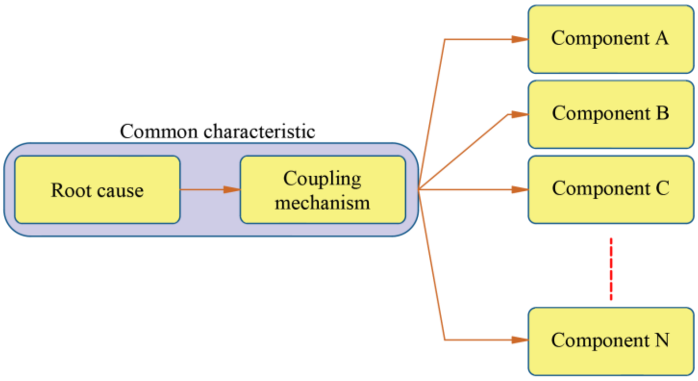


*Figure 13. Dependent event elements.*

## 6. CONCLUSION

In this review study, different aspects of power systems reliability analysis are discussed, and details regarding to the modelling and evaluation are described. Most common methods and approaches are explained. In conclusion, the reliability analysis for power system helps to increase the quality of supplied energy, supply adequate energy to customers and gain their trust. The reliability analysis is necessary to perform a running and future assessment of power system to decrease the operation and investment cost, to decrease failures and to increase security. It is also clear that reliability analysis is crucial on modern power system which is becoming more complex. As a future work, reliability analysis and evaluation methods for modern power systems such as microgrids and nanogrids could be investigated.

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