Chapter 8
Reliability in Smart Grids with Energy Storage Systems

8.1 Reliability in Power-Energy Systems

A reliable supply of electricity with the requisite high quality to industrial consumers, in particular, is essential for society's continued development and welfare. The standard DIN 40 041 defines reliability as an entity's quality in terms of being able to meet the demand for reliability during or after specified time intervals and under specified conditions of use. The electricity supply is considered to be reliable when it continuously meets customer demand (just-in-time), and this must be so while the complete system of primary-energy production, conversion, transport and distribution are always necessarily factored in. Various malfunctions or events characterized by their intensity (insufficient energy) and duration also affect the security of supply in various ways, e.g. affecting varying numbers of consumers. Causes of malfunctions are external, e.g., storms and lightning strikes, terrorism or solar winds, or internal, e.g., planning and design errors or operational errors such as overloaded system components, short circuits caused by incorrect operation, switching surges, and have various points of origin. Statistical data on this are plotted in unavailability graphs, see, e.g., Fig. 8.1. Malfunctions that go undetected or cannot be assigned to any of the predefined groups/criteria are placed under the category "no identifiable cause" [1].

The acceptable limit for permissible durations of a malfunction (as a function of the unavailable quantity of power) is presented in Fig. 8.2. Smaller malfunctions (of only kilowatts of power unavailable because of a malfunction) have a longer acceptable interruption time, even up to hours. Major malfunctions may not exceed the acceptable interruption time, normally of just seconds.

The quality of the power supply is specified by a variety of factors including:

- service quality,
- voltage quality, and
- supply reliability.

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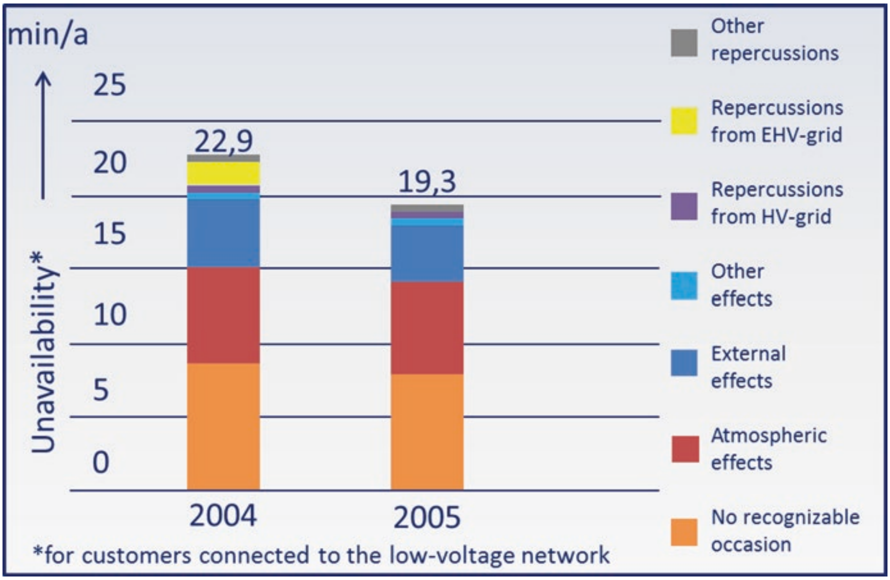

Fig. 8.1 Trend of energy unavailability in Germany 2004–2005

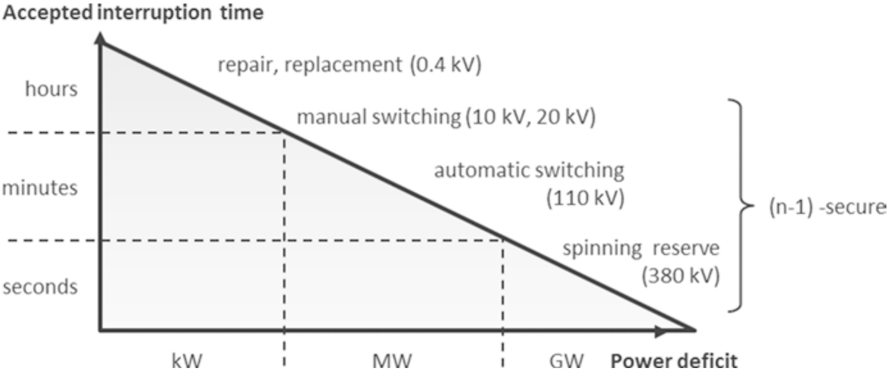

Fig. 8.2 Acceptable interruption duration as a function of supply interruption (power unavailability) based on a Zollenkopf curve [2]

Service quality is the quality of services provided by an energy supplier to consumers before and during an existing contractual relationship. Quality of voltage is defined by national and international standards such as EN50160 (medium and low voltage) and the grid code (high and ultra-high voltage). They define grid-parameter features such as acceptable voltage range, which may not exceed ±10 % of the nominal voltage. Predefined frequency conditions also apply to synchronous systems so that a range of 49.5 Hz ≤ f ≤ 50.5 Hz is guaranteed for 99.5 % of the time and 47 Hz ≤ f ≤ 52 Hz for 100 % of the time. Supply reliability is expressed as

Table 8.1 Supply reliability parameters [3].

Parameter	Symbol	Unit	Values for Germany in 2012
Interruption frequency (number of interruptions per customer per year)	H_U	[1/a]	0.28
Interruption duration (average duration of a supply interruption)	T_U	[min]	15.9
Unavailability (average total length of all supply interruptions per customer per year)	Q_U	[min/a]	4.45

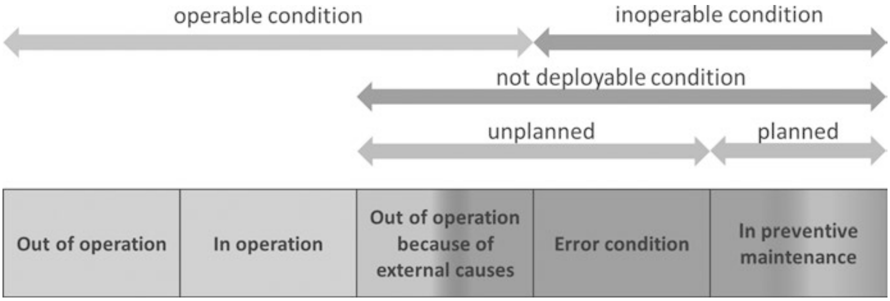

Fig. 8.3 Operating state classification

a measure of an electric-power system's capacity to supply customers sufficiently. Supply reliability identifies the number and duration of supply interruptions, the main parameters being operability, maintainability and maintenance support, see Table 8.1.

All of the system components (equipment) and their states are specified and defined. There are two states: operating or not operating, which occur either as scheduled (servicing) or unscheduled (malfunction), see Fig. 8.3.

The transparent variable of supply reliability is expressed by the supply-interruption duration/energy unavailability (in minutes) per calendar year and analyzed statistically. As Fig. 8.4 [1] shows, European countries have a range of supply-reliability indices. Power was unavailable for 14.9 minutes in Germany in 2010 and more than ten times longer (193 minutes) in Finland. The differences are generally due to different grid structures, equipment, components and systems and operating modes.

8.2 Grid-Reliability Calculations

Reliability is the capability of a component or system to perform its required function without failure—under given conditions for a given time interval [3]. Reliability is relevant to highly complex systems consisting of numerous components. The

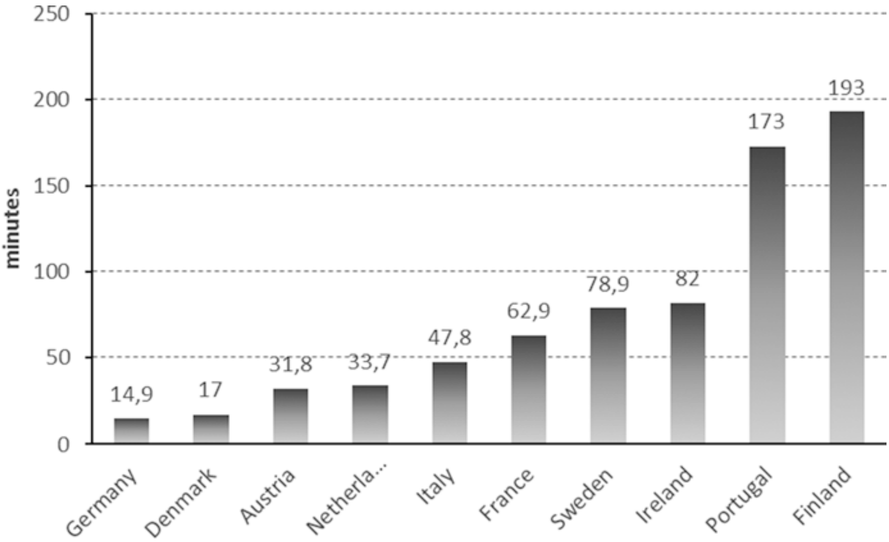

Fig. 8.4 Supply interruptions in European nations in 2010 [4]

reliability of a complete system is contingent on the reliability of the individual system components and equipment, as well as their interconnections. Stochastic processes are used to model each system component, i.e., its state, in time domains. Only one state (operating or not operating) is possible at any time, see Fig. 8.5.

Components have other specific parameters defined on the basis of manufacturers' experiences with tests and real operation over a specified time. These include:

- mean time to failure (MTTF), the expected time of failure measured from the time of a completed repair,
- mean time to repair (MTTR), the expected time needed to repair an element measured from the time of failure until its repair,

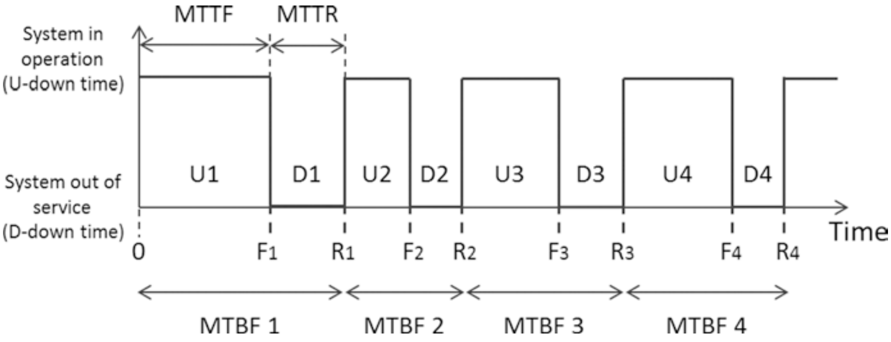

Fig. 8.5 Operating states of elements over time

- mean time between failures (MTBF), the average time between successive failures expressed as the total of MTTF and MTTR in Eq. (8.1):

$$MTBF = MTTR + MTTF \tag{8.1}$$

- expected failure rate λ and expected repair rate μ related to the MTTF and MTTR as in Eqs. (8.2) and (8.3), respectively, indicating the number of failures $\mathrm{n}_{\mathrm{f|T}}$ and repairs $\mathrm{n}_{\mathrm{r|T}}$ in the given period of observation T, where $\mathrm{t}_{\mathrm{TFi}}$ is the time to ith-failure and $\mathrm{t}_{\mathrm{TRi}}$ is the time to ith-repair

$$\lambda = \frac{1}{MTTF} = \frac{n_{f|T}}{\sum_{i=1}^{n_{f|T}} t_{TFi}} \tag{8.2}$$

$$\mu = \frac{1}{MTTR} = \frac{n_{r|T}}{\sum_{i=1}^{n_{r|T}} t_{TRi}} \tag{8.3}$$

These standard parameters furnish the basis for calculating the two basic parameters of availability A and unavailability U, which are the starting point for creating the base model of components. These parameters can be calculated by observing the operating waveform where t_{up} indicates all interval durations of element operation and $\mathrm{t}_{\mathrm{down}}$ its outage or failure or by using the aforementioned parameters, see Eqs. (8.4) and (8.5):

$$A = \frac{\sum t_{up}}{\sum t_{up} + \sum t_{down}} = \frac{MTTF}{MTTF + MTTR} = \frac{\mu}{\mu + \lambda} \tag{8.4}$$

$$U = \frac{\sum t_{down}}{\sum t_{up} + \sum t_{down}} = \frac{MTTR}{MTTF + MTTR} = \frac{\lambda}{\mu + \lambda} \tag{8.5}$$

Distribution Functions and Parameters

Since reliability parameters normally represent average rather than current values, they are normally defined by random numbers, which, in turn, are specified by probability-distribution functions. Typical distribution functions are:

- probability distribution,
- exponential distribution, and
- Weibull distribution.

Probability Distribution Functions

A probability distribution function f(x) has a related probability density function f(t) that represents the probability of random variable x having a specific value. This f(t) function specifies a component's probability of failure after the time t has passed. Depending on the type of component, the f(t) function can represent various expressions, but it always returns a value between 0 and 1. The integral of the probability-distribution function over all possible results is equal to 1, because each random occurrence has one actual outcome, which is presented in Eq. (8.6):

$$\int_{-\infty}^{\infty} f(x)\,dx = 1. \tag{8.6}$$

The component cumulative distribution function F(t) describes the probability that an element will have failed once the time t has passed. This is expressed by Eq. (8.7):

$$\boldsymbol{F(t) = P(T_f \le t) = \int_{0}^{t} f(x)\,dx; \quad t > 0,} \tag{8.7}$$

where F(t) is the cumulative distribution function and T_f is the element's time to failure.

The probability that time values in the reliability calculation are negative is 0, and the probability that the duration is less than infinity is equal to 1, as presented in Eq. (8.8):

$$\mathrm{F}(0) = 0; \qquad \mathrm{F}(\infty) = 1. \tag{8.8}$$

The hazard function λ(t) is closely related to the probability-density function and the cumulative distribution function. The hazard function represents the probability of an element's failure if it has not already failed. Since the density function represents the probability that an element will fail and the cumulative distribution function represents the probability that an element has failed already, the hazard function is expressed by Eq. (8.9). An example of the hazard function is the bathtub curve that describes changes in an aging component's failure rate. Hazard functions are therefore identical to failure rate functions [1].

$$\lambda(\boldsymbol{t}) = \frac{\boldsymbol{f(t)}}{1 - \boldsymbol{F(t)}} \tag{8.9}$$

The reliability function R(t) expresses the probability that a component will function until a specific time and is represented by Eq. (8.10) [DISS BA]:

$$\boldsymbol{R(t) = 1 - F(t) = P(T > t).} \tag{8.10}$$

Probability distribution functions are characterized by the statistical metrics of mean values, variances and standard deviations. The value obtained is the geometric mean of the function and can be calculated with Eq. (8.11). Variance measures the function's variation around the mean, as in Eq. (8.12). The square root of the variance is the standard deviation specified in Eq. (8.13) [1].

$$\boldsymbol{\textit{Expected value} = \bar{x} = \int_{-\infty}^{\infty} x f(x)\,dx} \tag{8.11}$$

$$\boldsymbol{Variance} = \boldsymbol{\sigma}^2 = \int_{-\infty}^{\infty} \left[\boldsymbol{f}\left(\boldsymbol{x}\right) - \bar{\boldsymbol{x}}\right]^2 \boldsymbol{dx} \tag{8.12}$$

$$\boldsymbol{Standard\ deviation} = \boldsymbol{\sigma} = \sqrt{\boldsymbol{Variance}} \tag{8.13}$$

Exponential Distribution

Exponential distribution has a constant hazard function and is therefore commonly used in reliability analysis. The hazard function represents an electrical component during its useful life. Exponential distribution is denoted by a single parameter of the failure rate λ. Examples of exponential distributions of reliability and failure rate over time are presented in Fig. 8.6. Exponential distribution can be calculated with Eqs. (8.14–8.18):

$$\boldsymbol{f}\left(\boldsymbol{t}\right) = \lambda \boldsymbol{e}^{-\lambda t}; \quad \boldsymbol{t} \geq 0 \tag{8.14}$$

$$\boldsymbol{F}\left(\boldsymbol{t}\right) = 1 - \boldsymbol{e}^{-\lambda t} \tag{8.15}$$

$$\lambda\left(\boldsymbol{t}\right) = \lambda \tag{8.16}$$

When additionally are:

$$Expected\ value = \bar{\boldsymbol{x}} = \frac{\mathbf{1}}{\lambda} \tag{8.17}$$

and

$$Variance = \boldsymbol{\sigma}^2 = \frac{\mathbf{1}}{\lambda^2} \tag{8.18}$$

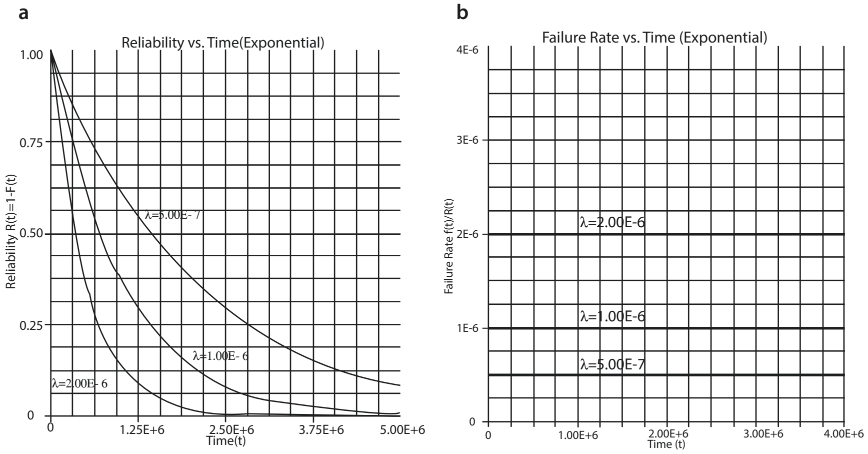

Fig. 8.6 Exponential distribution of (**a**) reliability over time; (**b**) failure rate over time [5]

Weibull Distribution

A Weibull distribution has two parameters, a scale parameter α and a shape parameter β that take on various forms in response to different data sets. A Weibull distribution is used to represent the early normal operation and wear-out period of a component's life cycle, as presented in Fig. 8.7 [5]. A Weibull distribution is defined by the formulas in Eqs. (8.19–8.21) [5]:

$$\boldsymbol{f}(\boldsymbol{t}) = \frac{\beta \boldsymbol{t}^{\beta-1}}{\alpha^{\beta}} \boldsymbol{e}^{\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)}; \quad \boldsymbol{t} \geq 0 \tag{8.19}$$

$$\boldsymbol{F}(\boldsymbol{t}) = 1 - \boldsymbol{e}^{\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)} \tag{8.20}$$

$$\lambda(\boldsymbol{t}) = \frac{\beta \boldsymbol{t}^{\beta-1}}{\alpha^{\beta}} \tag{8.21}$$

where α is the scaling factor and β is the shape parameter [1].

Methods

Analysis and simulation methods have long been employed to calculate reliability, see Fig. 8.8. Selection of the right method depends on various factors. Factors such as the size of the electric power system analyzed (number of nodes, topology), its dependence on connected components (every component being dependent on another) and the number of use cases (larger systems having more use cases) play a major role.

The analysis methods are either state-space methods or network methods. State-space methods are, in turn, either combinatorial methods or Markov processes and consider every possible grid state. A system can be in only one state at any given

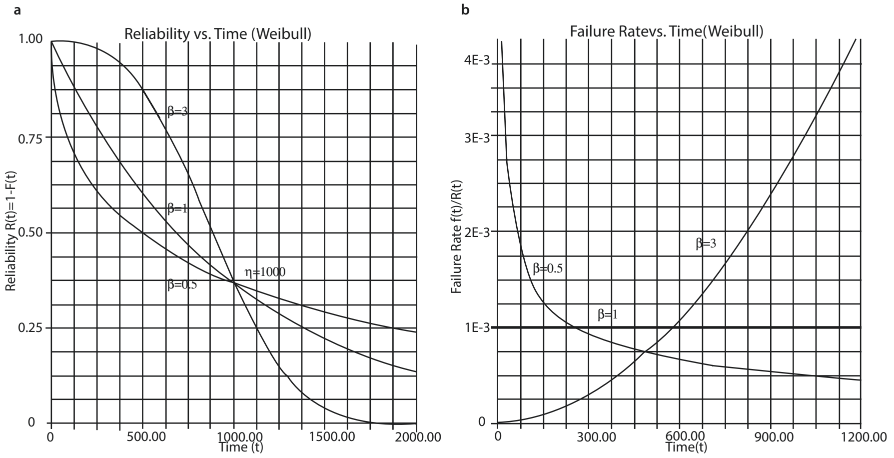

Fig. 8.7 Weibull distribution of (**a**) reliability over time; (**b**) failure rate over time [5]

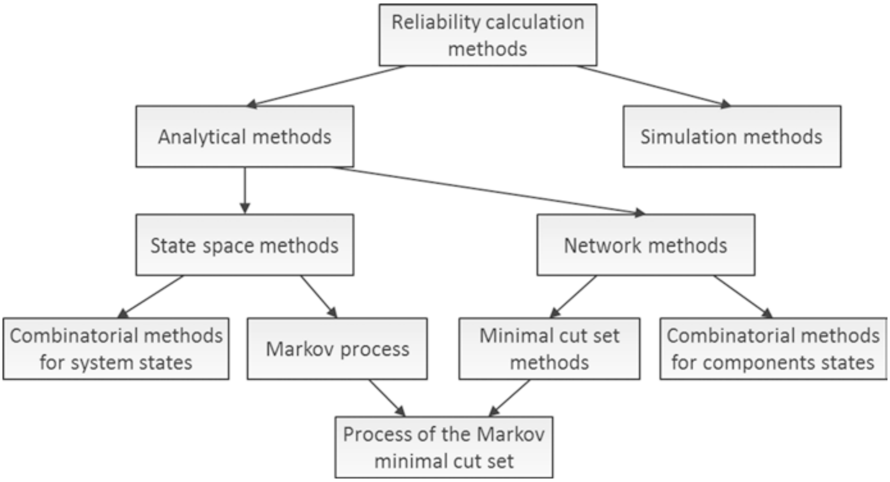

Fig. 8.8 Methods for reliability calculation [6]

time. Stochastic processes are used to model and calculate the transitions between every state. The combinatorial method uses the probabilistic relationships between elements of systems to ascertain all possible system states. In Markov processes, a system's state in time is solely a function of its preceding state. An element is characterized by one of two states, "operating" or "not operating". The transition probabilities from one state to another are the failure rate λ and the repair rate μ, which are the reciprocals of the analyzed component's MTTF and MTTR, respectively. Some elements can have more than two states. Estimating future probabilities for every state requires specifying the state-transition probabilities from every state Zj to one state Zm, starting with the initial state. The transition probability is treated as a matrix [P(t)] and represented by Eq. (8.22):

$$P(t+\Delta t)=[P(t)]\cdot P(t) \tag{8.22}$$

where [P(t)] is the matrix of transition probabilities from t to t+Δt, and P(t) is a vector of state probabilities at the time t.

Network methods are well-suited for modeling complex power systems with multiple components. Every element is represented as operating or not operating. Network methods subsume combinatorial methods for system states and minimal cut-set methods. Simulation methods are dominated by Monte Carlo methods, which can be completed sequentially or non-sequentially. They assess reliability by simulating a process and random system performance factoring in various variables in each simulation step. These include the number of failures, time between failures and various resupply times. Random numbers converted by a distribution function reproduce the performance of individual components. The quality of the results is contingent on the simulation cases. The larger the number of simulation cases, the better the results can be expected to be.

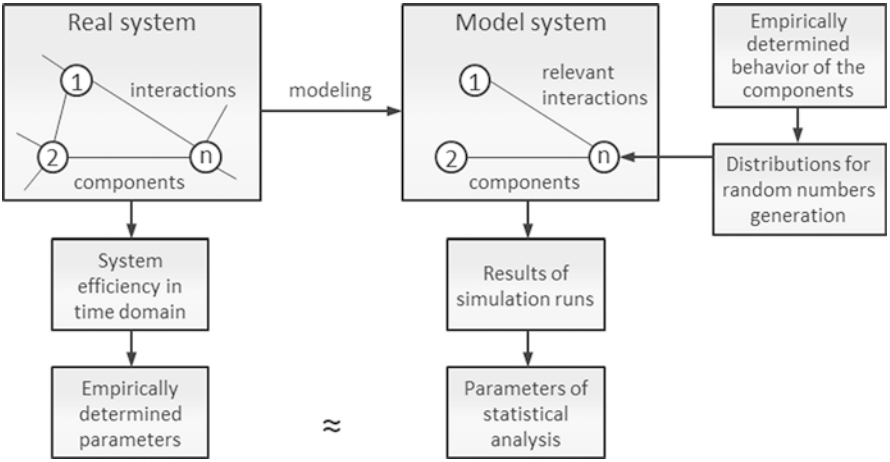

Fig. 8.9 Principle of a Monte Carlo simulation of electric power systems [6]

The principle of the Monte Carlo simulation is illustrated in Fig. 8.9. First, a stochastic model is developed based on the real system model (components and the interactions and interrelationships). Then, random variables are generated, which are used in multiple simulations of random processes. Statistical analysis of the simulated processes ultimately delivers the results. The Monte Carlo method has two fundamental advantages. Running a simulation with the same input data several times will not necessarily deliver the same results. Repeating the simulation can generate the distribution functions of the results, which make it possible to observe deployment of the reliability indices. Moreover, Monte Carlo methods can be used to assess the influence that the time required for necessary repairs of malfunctioning components has on the reliability of the overall system.

The optimal method for a particular system is ascertained by analyzing the parameters and criteria case by case. The aforementioned methods are compared in Table 8.2. Monte Carlo simulation requires more computation than analysis methods. This is reflected in the computation time. Moreover, the Monte Carlo method analyzes every possible state, while other methods do not.

Table 8.2 Comparison of reliability-modeling methods

	Monte Carlo simulation	Analysis methods
Computation time	Long simulation times	Dependent on simplification
Result	Dependent on simulation steps and random number generator Complete probability distribution of reliability indices	Constant expected value
System simulation	Every state is analyzed	Only significant states are analyzed

Table 8.3 Select reliability indices

Customer-based indices	
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
CAIDI	Customer Average Interruption Duration Index
ASAI	Average Service Availability Index
ASUI	Average Service Unavailability Index
EENS	Expected Energy Not Supplied
CAIFI	Customer Average Interruption Frequency Index
CTAIDI	Customer Total Average Interruption Duration Index
CEMI_n	Customers Experiencing Multiple Interruptions
MAIFI	Momentary Average Interruption Frequency Index
Load-based indices	
ASIFI	Average System Interruption Frequency Index
ASIDI	Average System Interruption Duration Index
Power quality indices	
SIARFI_x	System Instantaneous Average RMS Variation Frequency Index
SMARFI_x	System Momentary Average RMS Variation Frequency Index
STARFI_x	System Temporary Average RMS Variation Frequency Index

Reliability Indices and Criteria

Various indices, which have been developed by diverse standards' bodies and are sometimes applied and defined nationally, are used to assess power-supply system reliability. The most commonly used indices (see Table 8.3) fall into one of three categories: customer based, load-based or power quality. Customer-based indices include system and customer criteria generally specified by interruption duration and interruption frequency. The load based indices of Average System Interruption Frequency Index and Average System Interruption Duration Index only apply to a system. Power-quality indices are used for system-based assessment of grid quality represented by an RMS.

8.3 Storage-System Reliability

8.3.1 *Case Study: Calculation of Storage-System Reliability*

Critical power-supply infrastructures and their components/equipment must be planned for the long term and operated with constant efficiency to ensure that security of supply is technically reliable and cost-effective. Reliability modeling plays a crucial role in the verification of the technical feasibility of components such as storage systems, as well as in investment-decision support and risk assessments of the aforementioned factors.

This 9-Bus IEEE benchmark network represents a portion of the Western System Coordinating Council (WSCC) [7]. A power infrastructure contains three generators, three transformers, three load points, nine electric nodes, six lines and three branches. The base KV levels are 13.8 kV, 16.5 kV, 18 kV and 230 kV. The line-complex powers are approximately hundreds of MVA each. As a test case, the WSCC 9-bus case is easy to control and additional devices have been added such as energy storage and a renewable source of energy, see Fig. 8.10. The configuration parameters of the system are given in Tables 8.4 and 8.5 and they are used as input data for simulation. The electrical components from the graphical representation can be identified in the table by their location between beginning node (n_b) and ending node (n_e) with assigned reliability parameters. Furthermore, the number of customers connected to a particular node and power available at that specific node are given. The WSCC 9-bus case has been extended through the integration of energy storage in bus 6 and an additional renewable-power source from wind turbines.

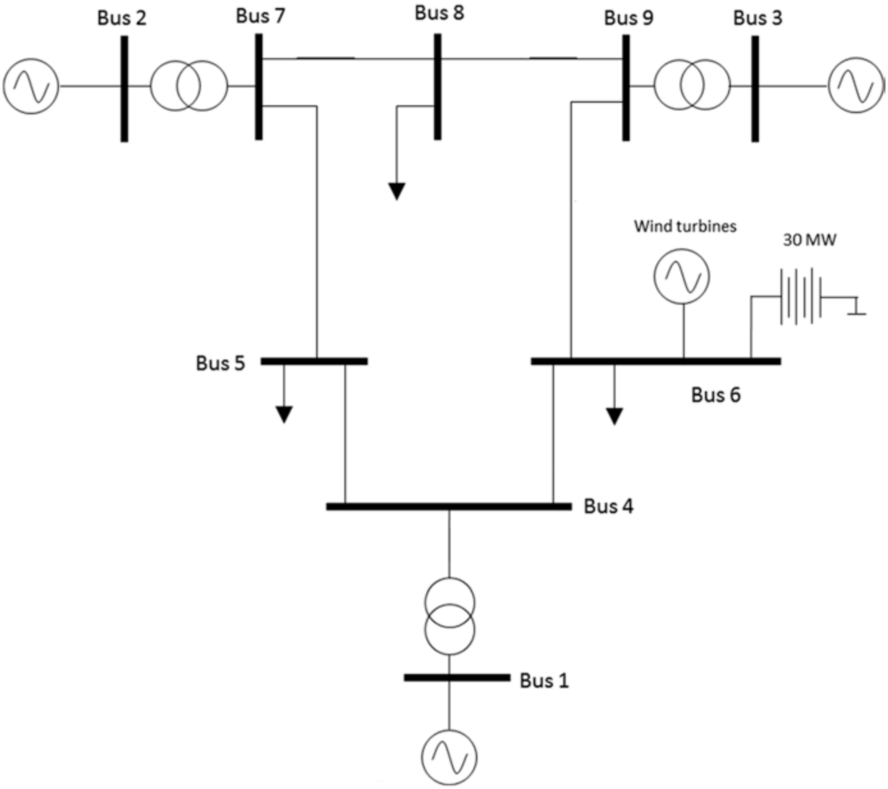

Fig. 8.10 9-Bus test system configuration

Table 8.4 Parameters used for 9-Bus test system—reliability indices

Reliability parameters					
Beginning node	Ending node	Failure rate of component	Time to repair without storage [h]	Time to repair with storage [h]	Failure rate of storage system
1	4	0.08	50	30	0.05
4	5	0.25	20	7	
4	6	0.25	20	7	
2	7	0.08	50	30	
7	5	0.25	20	7	
7	8	0.25	20	7	
3	9	0.08	50	30	
9	8	0.25	20	7	
9	6	0.25	20	7	

Table 8.5 Parameters used for 9-Bus test system—components configuration

Number of the node	Power available at particular node [MW]	The power of connected customers [MW]	Number of customers connected to node
1	72	0	0
2	163	0	0
3	85	0	0
4	0	0	0
5	0	125	90,000
6	15 wind, 30 storage	90	60,000
7	0	0	0
8	0	100	70,000
9	0	0	0

The modeling of connected electrical systems and storage installations based on complex network theory was carried out on the example of a 9-Bus power system. In order to estimate the indices reliability of the power system, the simulation approach based on the Monte Carlo method was implemented. The Monte Carlo simulations have been performed for the total sample of N = 100 years with a simulation time in sequence T = 1 year = 8760 hours. The algorithm generates a random loss of element in a power system. On that basis, the time to repair an element in every year is calculated. The calculations are carried out for a period of 100 years and, based on these calculations, a histogram can be created. The energy storage can be used as additional component of grid that improves the reliability of the electrical system. In case the line is inoperative, the energy storage can partly cover the energy demand, depending on the grid situation and structure. The customers are still being supplied with electricity, and the reliability indices are better than without the storage system. In order to determine the reliability of the grid, the power flow was not carried out. The simulation based on the history of grid's condition and number of failures of each component of the power system. Therefore, the size of the energy storage will affect the value of the reliability indices. In the example, the storage with installed power of 30 MW was used. The installation can provide 30 MW of power for one hour (30 MWh) during the failure of the power system. Availability of power from energy storage and its respond time are closely affiliated with the technology of integrated energy storage. In the case of simulation, the technology of energy storage is based on the lithium-ion battery. Since lithium-ion technology is characterized by a time of respond, which is very short for this kind of technology, this allows for a quick response in case of failure, and the rate of changes in the system is reduced [3]. Other solutions such as hydro-power pump and CAES have larger capacities of power and longer charging times, but the time to respond to failure is much longer than in lithium-ion energy storage [8].

In modeling the both the electrical and the storage system, some assumptions were made. Since the method is probabilistic and power flow is not calculated, the parameters of electrical components such as transformers, lines and generators are reduced to checking their operational availability. Failure rates of these elements were selected in accordance with recognized values for their type and voltage-level operation. Repair times also depend on many factors like type of failure, maintenance resources of the operator and weather conditions.

The reliability indices are graphically presented as histograms demonstrating the distributions of data. The adjacent bars on the histogram determine intervals of values, and their length quantifies the frequency of the observations in the interval. For the representation of obtained results, each bar includes a range of values from several sequences of simulation.

The distributions of indices are the most valuable means to evaluate the system with regard to the assessment of system reliability. Based on input data and configuration of the electrical power system (EPS), the reliability indices achieved very high values, which prove that the system is very reliable. Regarding EPS with storage system, the reliability indices are even greater, which demonstrates that the storage contributes to improving the reliability of the electric network.

The distributions of reliability indices for the 9-Bus system are presented in Fig. 8.11. The reliabilities for electrical power systems (EPS) without storage systems are represented with grey bars, and blue bars indicate results for the electrical power system with storage system. It can be noticed that the obtained results for the system supported by energy storage possess better reliability indices than that of the electrical system without storage installation (SI). SAIDI index for SI at point 0.0 has a height of 72, which mean that in 72 out of 100 years, the system average interruption duration was 0 hours. The value for EPS at the same point is 66 years without interruption. Also there are more blue SI bars close to zero-interruption hours a year than the grey bars of the EPS system which indicates fewer number of hours when customers are not supplied.

SAIDI is the **System Average Interruption Duration Index**, and it measures the total duration of an interruption for the average customer during a given time period. It is normally calculated for the period of one year and results in the number of customer minutes or hours of interruption. According to Fig. 8.11, the SAIDI index produces higher values when storage system is connected to the electric network. This effect is caused by energy-storage properties. When there is a loss of voltage, storage can temporarily supply customers, which causes increase reliability for the whole system. So a SAIDI index for a system connected with storage system (blue bars) is higher than a SAIDI index representing for a system without energy storage (gray bars). The reliability of a system and the height of the bars depends on the energy storage that is used.

SAIFI is the **System Average Interruption Frequency Index**, which provides the average number of interruptions in the system that a customer experiences during the observation period, normally calculated for 1 year. The SAIFI index results remain nearly the same for both systems, since only the duration of failure has been changed, while the number of failures remains the same.

CAIDI, the **Customer Average Interruption Duration Index,** represents the average time required to restore service after an outage occurs, which indicates how long an average interruption lasts. It measures the duration of time that the customer is de-energized per interruption. Assuming that energy storage exists in the system,

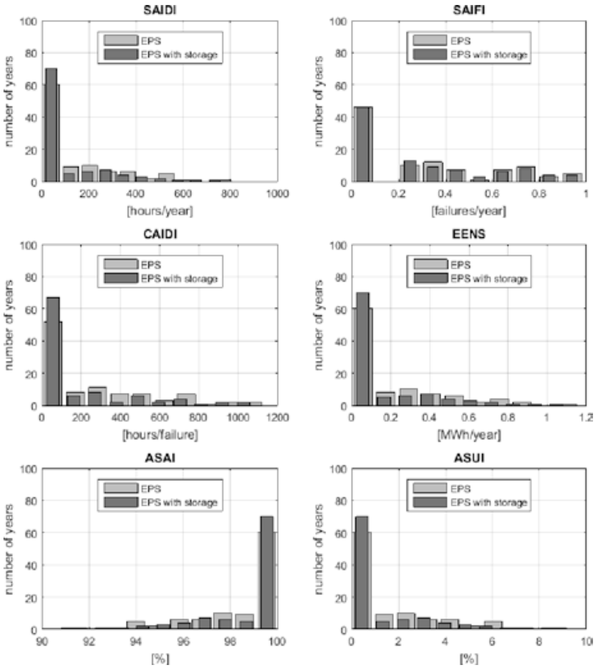

Fig. 8.11 Reliability indices distributions of the 9-Bus test system

the reaction to occurring faults is faster and, thus, the durations of customer interruptions are shorter, which is reflected in the CAIDI index. Therefore, an EPS with energy storage yields better results.

ASAI is the **Average Service Availability Index,** which is the ratio of total time in which a customer was energized during the observation period to the total time of customer service demanded. The average service availability index ASAI is expressed as a percentage so, where the distribution bars are concentrated close to 100 %, this means that the overall reliability of the system is very high.

ASUI, the **Average Service Unavailability Index,** represents the fraction of time that service was not available for the customer of the total customer hours demanded. The ASUI index clusters close to zero for cases in which the system is mostly unavailable.

EENS, the **Expected Energy Not Supplied** indicates the amount of unsupplied energy to the customer in the system due to power interruptions. According to EENS index value, the energy not supplied to the customers is close to zero, but the EPS is normally more reliable with additional source of energy in this cas EES., and for indicate with energy storage the value is higher, it means. The dependence on EES is clearly reflected in the EENS index.

In order to present the histograms of the system-reliability indices, which refer to the values of the failure rates of the components, the values were assumed to be much worse that those in reality. The duration of the system failure and repair time have also been extended. For the purpose of simulation, the average time of failure

Table 8.6 Reliability-related parameters vs storage technologies

Storage technologies	Supply reliability		Voltage quality		Service quality
	Short-term phenomena (interruptions)	Long-term phenomena	Short-term phenomena (e.g., flicker, harmonics)	Long-term phenomena's (e.g., voltage profile)	
Chemical storage systems (e.g., batteries)	+	+/−	+	+/−	+
Electrical storage systems (e.g., super caps)	+	−	+	−	+
Mechanical storage systems (e.g., pump storage)	+/−	+	−	+	+
Thermal-storage systems	−	+	−	+	+

per customer is expressed in hours (1–10 h). In fact, in European countries, these times are given in minutes, and it ranges between 15–500 min/year/customer.

Based on this simulation case, it can be summarized that energy storage supports the power system in order to maintain the reliability of the power flow in the network. Customers may be exposed to disruptions during the occurrence of a failure of the power system. When the failure appears, power systems will be not able to supply some customers. To reduce the amount of customers that are affected by disruption of electrical grid component, the system can be equipped with devices such as storage energy to supply recipients. Thus, the additional sources will increase the reliability of the system and cause fewer customers to be exposed to disruptions. The energy storage contributes to the improvement of reliability of the system. Type of storage, technology and costs depends on many factors. In order to select the appropriate energy storage, proper analysis must be carried out because, e.g., not all storage-system technologies have the technical properties to fulfil the requirements defined by the relevant use case, see Table. 8.6.

Test Questions Chap. 8

- What is meant by the phrase “power-system reliability”?
- What kind of criteria describe reliability?
- What is the level of reliability of power systems in European countries today?
- What are the kinds of reliability-calculation methods?
- What kind of storage parameters should be taken into account when calculating power system reliability?

References

1. Arendarski B (2015) Reliability assessment of smart grids. Dissertation, Magdeburg. ISBN 978-3-944722-32-0
2. Zollenkopf K (1968) Diskussionsbetrag zu Cigre-Tagung. Gruppe 32. ETZ Bd 89: 734
3. Billinton R, Allan R (1996) Relaibility evoluation of power systems, 2nd edn. Springer Science + Busines Media, New York
4. Council of European Energy Regulators (2014) CEER Benchmarking Report 5.1 on the Continuity of Supply, Feb 2014
5. Common Relaibility Distributions (2001) Alion science and technology. System Relaibility Centre, New York
6. Haubrich H, Seitz T, Montebauer A (1994) Zuverlässigkeit. AKTR Seminar, RWTH Aachen
7. Information Trust Institute Illinois Center for a Smarter Electric Grid (ICSEG). http://icseg.iti.illinois.edu/. Accessed 7 Oct 2016
8. Komarnicki P (2016) Energy storage systems: power grid and energy market use cases. Journal Archives of Electrical Engineering. Publisher Polish Academy of Sciences, Warsaw, Vol. 65, Issue 3 doi:10.1515/aee-00101-2016-01: 495–511