Chapter 6

Assessment of Reliability of Composite Power System Including Smart Grids

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Additional information is available at the end of the chapter

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Abstract

The large service interruptions of power supply in the transmission system have significant impact on modern society. The aim of the power system engineers is to prevent and mitigate such events with optimal decisions in design, planning, operation and maintenance. Due to the rapid growth in the power demand and competitive power market scenario, the transmission and distribution systems are frequently being operated under heavily loaded conditions. This tends to make failure of components more frequent in the power system necessitating large downtime to repair or replace the equipment. A majority of the service interruptions are happening due to lack of proper planning and operation of power system. Therefore, complete reliability assessment in generation, transmission and distribution systems is needed at the planning stage. The reliability assessment in smart grids is very much beneficial to the power operator and reduces the risk of grid failure due to failure of major components in power systems. This chapter is confined to composite power system reliability assessment. The composite power system combines both the generation and transmission systems' adequacy. The generation system in the composite power system includes both conventional and renewable sources. The composite power system reliability assessment is quite difficult due to the large number of equipment, interconnected network topology and uncertainties in generation capacity. The reliability assessment concentrates mainly on the use of probabilistic states of components in generation and transmission systems to evaluate the overall reliability. This analysis will result in a cost-effective system configuration to provide continuous power supply to the consumers at reasonable cost. The reliability level of the system is measured by the defined indices. One of these indices is the probability of average power availability at load bus. This reliability assessment mainly focuses on development of methods to evaluate the probability of average power availability at load buses for a specified system configuration. This chapter discusses the two main techniques called node elimination method and modified minimal cut set method.

Keywords: composite power system reliability, failure rate, repair rate, minimal cut set, Monte Carlo simulation

1. Introduction

The modern power system has become a highly complex network, due to the integration of a large number of generating sources and large transmission and distribution networks. The above-stated reasons will affect the reliability of the smart grid. The main requirement of the power system is to provide electricity for a wide range of consumers with various requirements. It is not possible to serve the consumers continuously due to the random failures of equipment in the power system network. This causes the consumers' service interruptions frequently irrespective of the planned maintenance. It affects the reliability of power supply at the consumer bus and smart grid as well. Therefore the power engineers must consider the term "reliability" at the level of designing and planning of the power system network or smart grid. Reliability is the general quality of the system and defined as "It is an ability of the system to perform a desired function within a specified period of time under stated conditions" [1].

In view of above-mentioned reasons, there is a need for complete reliability assessment of the present power system. The evaluation of reliability plays an important role in power system analysis, design, upgrades and operations, especially in bulk power system. Power system reliability assessment methods have been developed over the years, and many publications are available on this subject [1–8].

2. Power system reliability assessment

The power system reliability is a measure of the ability of the system to meet the consumer requirements with quality electrical energy. In general "reliability" is usually divided into two aspects of system adequacy and system security [9, 10], as shown in **Figure 1**.

According to the North American Electric Reliability Corporation (NERC), adequacy and security are defined as [11]:

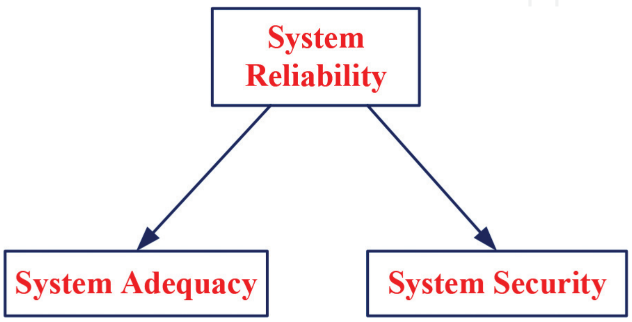

Figure 1. Power system reliability subdivision.

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Adequacy—"The ability of the power system to supply the total electrical demand and power requirements of the end use customers at all times, by taking into the account of scheduled and reasonably expected unscheduled outages of system components."

Security—"The ability of the power system to withstand sudden disturbances such as electric short circuits or unexpected loss of system elements."

The work reported in this chapter is limited to adequacy assessment of the power system. The fundamental techniques used for the assessment of adequacy can be categorized in terms of their application to segments of a complete power system. These segments of the power system are shown in **Figure 2** and can be defined as the functional zones of generation, transmission and distribution [12]. Hierarchical levels are formed by combining the functional zones of the power system.

The assessment of reliability at hierarchical level I (HL-I) is only concerned with the generation facilities. In this level, the total power system generation including interconnected renewable generation is examined to decide its ability to serve the total system load demand considering the possible contingencies. The reliability assessment at HL-I is usually defined as generating capacity reliability assessment. The reliability assessment at hierarchical level II (HL-II) combines both the generation and transmission in evaluation of the integrated ability of the composite power system to deliver energy to the bulk supply points. This analysis is generally termed as composite power system reliability assessment or bulk power system reliability assessment. The reliability assessment by considering all the three functional segments is

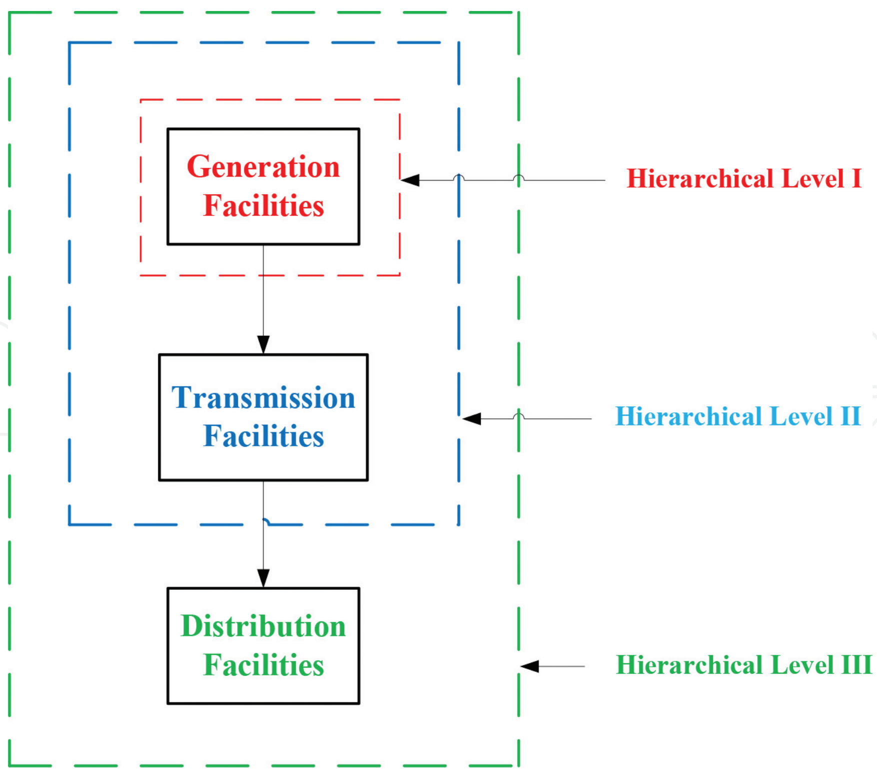

Figure 2. Structure of hierarchical level.

known as HL-III analysis. The work reported in this book is confined to the reliability assessment at HL-II level (composite power system) and is focused on adequacy analysis.

The basic role of an electric power system is to supply its customers with electrical energy as economically as possible and with a reasonable degree of continuity and quality. Power system reliability is generally expressed in terms of indices that reveal the system capability and the quality of service provided to its customers. The reliability concept and techniques first applied on practical power systems were mostly based on empirical experience and were all deterministically based. Many of methods are still in use today. These earlier concepts of reliability assessment, however, are inherently deterministic and do not account for the probabilistic or stochastic nature of system behavior, customer demands or component failures. The application of probabilistic methods for reliability assessment can consider the inherent stochastic nature of the power system and provide quantitative measures for power system reliability and thus complement the limitations of deterministic methods. Power system reliability assessment using probabilistic methods has been in practice since 1947. These are discussed in detail in the following sections. Research on reliability assessment over the last 60 years has been directed toward the evaluation of reliability indices applying probabilistic methods [13, 14]. Many reliability indices are defined over the years to judge reliability of the power system. The most commonly used reliability indices are discussed in [15]. The research work reported in this book is mainly focused on the average power availability for the bulk consumers connected to the power system network.

3. Literature review

The main function of the modern power system is to satisfy the energy needs of the consumer as economical as possible and with reasonable level of continuity and quality. The power system is made up of different components like circuit breakers, transformers, relays, etc. Failure of these components will result into customer supply interruption and cause loss of load. In order to assess the continuity of power supply to the consumers and improve it if possible, there is need of complete reliability assessment. By considering the failure (λ) and repair (μ) rates of all the components in the system, the average power availability is calculated with tracing of power flow paths. This is a basic method followed by power engineers earlier [1–14]. After tracing of paths, the equivalent failure and repair rates are calculated by series-parallel approach. But in the present complex power system, it is very difficult to identify those paths. Later star-delta and delta-star conversion methods developed, but again identification of those networks is a difficult task in complex systems [14]. The reliability of any system is determined using either deterministic or probabilistic methods. Deterministic methods present the reliability assessment with the information on how a system/component failure (called contingencies) can happen or how system/component success can be achieved. The traditional deterministic criterion used particularly in bulk electric systems (BES) is known as the N-1 security criterion [14] under which the loss of any bulk system component will not result in system failure. The main weakness of deterministic method is that they do not react to the stochastic nature of power system behavior, consumer demands or component failures. Power

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system behavior is stochastic in nature, and therefore it is reasonable to believe that the probabilistic methods are able to react to the real factors that influence the reliability of the system. Probabilistic methods present quantitative indices (reliability indices), which can be used to make a decision on whether the power system performance is acceptable or if changes need to be made.

An analytical method will constantly give the same numerical result for the same system, same model and same set of input data. Hence these methods tend to provide a high degree of confidence in the reliability assessment. Analytical methods, however, usually need assumptions to simplify the solutions. This is particularly the case with complex network and generating system with integration of renewable generation. The resulting analysis can therefore lose some of the confidence on the results obtained. This difficulty can be reduced or eliminated by using a simulation approach. Monte Carlo simulation method is a well-known method and is used to estimate the reliability indices by simulating the actual process and random nature of the failure and repair of the system/components. This method, therefore, treats the problem as a series of experiments. There are advantages and disadvantages in both methods. Generally, Monte Carlo simulation method requires a large computation time compared to analytical methods. Monte Carlo simulation methods, however, can theoretically take into account virtually all aspects and contingencies inherent in the planning, design and operation of a power system [12, 14].

Considerable research has been done in the last two decades in the area of composite power system reliability assessment using analytical, Monte Carlo simulation and mixing of both methods [1–14]. There are two types of Monte Carlo methods, such sequential and nonsequential types. Nonsequential method is widely used in the evaluation of power system reliability. The research work presented in this book is mainly concentrating on the difficulties associated with the traditional methods and presented some simpler methods for reliability assessment.

4. Composite power system reliability assessment

The research work presented in this book concentrates on HL-II, i.e., composite power system reliability assessment. These reliability studies will assess the ability of the composite generation and transmission system (composite power system) to not only satisfy the consumer requirements but also tolerate the random failures and execute preventive maintenance of electrical components. The reliability performance of any system is generally evaluated by the reliability parameters or indices. The composite power system reliability is judged in this research work by considering “average power availability” and “loss of load expected” as reliability indices at the bulk consumer buses. There are many publications that are dealing with composite power system reliability assessment [1–14]. In the evaluation of reliability in composite power system, many technical issues are involved such as load uncertainty, generation adequacy, integration of nonconventional sources, multiple outages, etc. [4, 13]. By keeping these technical issues in view, this research work addresses some new and improved methods for the assessment of composite power system reliability.

The composite power system reliability assessment presented in this book considers all equipment in the system such as circuit breakers, transformers, generators, buses, lines, etc.

5. Reliability assessment techniques

The electric power systems are good examples for reliability assessment. In many power systems, the average duration of interruptions faced by a customer is just a few hours per year, which indicates that high availability of power supply to consumers is ensured considering scheduled and unscheduled outages (random failures). The high power availability can be achieved by proper maintenance and monitoring of the equipment. There are several methodologies developed over the years for the reliability measurement. The early methods used were all deterministic and are not convenient to apply for large interconnected power system. Also the deterministic methods cannot consider the stochastic nature of the system and load [14].

Later probabilistic methods are developed to obtain meaningful information regarding the system reliability. The probability of random failure and repair durations during the operating life of the component is assumed to be exponentially distributed. Based on this, the mean time to failure (MTTF = $1/\lambda$) and the mean time to repair (MTTR = $1/\mu$) can be evaluated [15]. These indices for each component are used to obtain the overall system reliability. In this chapter, the average power availability at the load bus is used as a measure for the reliability assessment of the system. The reliability study in the interconnected power system is complex due to the large number of components and network topology. So far the reliability assessment in interconnected power system is achieved through tracing of the power flow paths [10–14]. But tracing of power flow paths in a large power system network becomes difficult and takes time. Simple and more convenient method based on electrical circuit approach is presented here.

The probability of power availability and unavailability of a component having failure and repair rates (λ and μ) is given in Eqs. (1) and (2). The failure and repair rates of each component in the power system are assumed to be constant throughout the operation. The probabilities of failure and repair rates are exponentially distributed. The component failure and repair rates are independent of other components, and their future states are not dependent on their past history. So the probability of present state changes is governed by the exponential distribution and not dependent on past history of the component.

$$Availability = \frac{\mu}{\lambda + \mu} \quad (1)$$

$$Unavailability = (1 - Availability) = \frac{\lambda}{\mu + \lambda} \quad (2)$$

The existing methods for the reliability assessment of composite power system are explained in the following chapters. The limitations and difficulties of those methods are also discussed.

5.1. Series-parallel approach

If two components are connected in series in a branch of the network and each component has its failure rate and repair rate as shown in **Figure 3**. The equivalent failure and repair rates for the branch are given in the Eqs. (3) and (4).

$$\lambda_{eq} = \lambda_1 + \lambda_2 \tag{3}$$

$$\mu_{eq} = \frac{\mu_1 \mu_2}{\mu_1 + \mu_2} \tag{4}$$

Similarly if two components are connected in parallel as shown in **Figure 4**, then the equivalent failure and repair rates are given in Eqs. (5) and (6).

$$\lambda_{eq} = \frac{\lambda_1 \lambda_2}{\lambda_1 + \lambda_2} \tag{5}$$

$$\mu_{eq} = \mu_1 + \mu_2 \tag{6}$$

Initially using this series-parallel approach, most of the simple power system network reliability was evaluated.

5.2. Star-delta approach

In the complex interconnected power systems, there exist a number of star and delta configurations, and series-parallel approach alone is not enough to reduce the network. During the evaluation of the availability, there will be a need for star-delta transformation for network

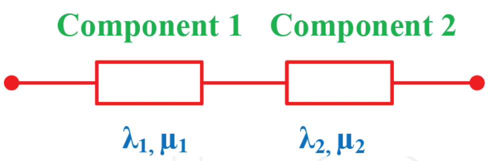

Figure 3. Components in series.

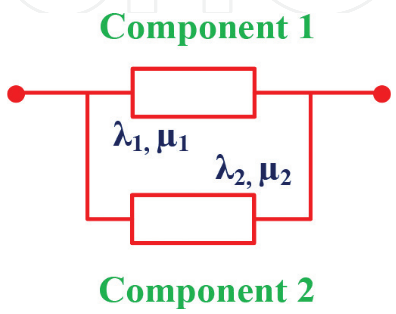

Figure 4. Components in parallel.

reduction. The equivalent failure and repair rate transformations from star to delta or vice versa are given in the following equations from Eqs. (7) to (12). The equivalents are based on the condition that the equivalent failure and repair rates for both the configuration should be same across any two terminals. The equivalent star-delta reliability models are shown in **Figures 5** and **6**.

The equivalent failure rates are given by

$$\lambda_{ab} = \frac{\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1}{\lambda_3} \tag{7}$$

$$\lambda_{bc} = \frac{\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1}{\lambda_1} \tag{8}$$

$$\lambda_{ac} = \frac{\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1}{\lambda_2} \tag{9}$$

Equivalent repair rates are given in the equations from Eqs. (10) to (12) as follows

$$\mu_{ab} = \frac{\mu_1\mu_2}{\mu_1 + \mu_2 + \mu_3} \tag{10}$$

$$\mu_{bc} = \frac{\mu_2\mu_3}{\mu_1 + \mu_2 + \mu_3} \tag{11}$$

$$\mu_{ac} = \frac{\mu_1\mu_3}{\mu_1 + \mu_2 + \mu_3} \tag{12}$$

5.3. Delta-star approach

Similarly the conversion from star to delta is as follows. The equivalent failure rates are given by equations from Eqs. (13) to (18),

$$\lambda_1 = \frac{\lambda_{ab}\lambda_{ac}}{\lambda_{ab} + \lambda_{bc} + \lambda_{ca}} \tag{13}$$

$$\lambda_2 = \frac{\lambda_{ab}\lambda_{bc}}{\lambda_{ab} + \lambda_{bc} + \lambda_{ca}} \tag{14}$$

$$\lambda_3 = \frac{\lambda_{ac}\lambda_{bc}}{\lambda_{ab} + \lambda_{bc} + \lambda_{ca}} \tag{15}$$

Equivalent repair rates are given by

$$\mu_1 = \frac{\mu_{ab}\mu_{bc} + \mu_{bc}\mu_{ac} + \mu_{ab}\mu_{ac}}{\mu_{bc}} \tag{16}$$

$$\mu_2 = \frac{\mu_{ab}\mu_{bc} + \mu_{bc}\mu_{ac} + \mu_{ab}\mu_{ac}}{\mu_{ac}} \tag{17}$$

$$\mu_3 = \frac{\mu_{ab}\mu_{bc} + \mu_{bc}\mu_{ac} + \mu_{ab}\mu_{ac}}{\mu_{ab}} \tag{18}$$

The interconnected power system network (IEEE 6 bus reliability test system) used here consists of a number of circuit breakers, two generating units and four load points as shown in **Figure 7** [15]. In this IEEE 6 bus reliability test system, the failure and repair rates (λ and μ) of each component are given in [15]. The average probability of power availability at load bus is calculated by reducing the network by series-parallel and star-delta or delta-star conversion methods between the source node and the sink or load node. The equivalent reliability model of the IEEE 6 bus reliability test system is shown in **Figure 8**.

In the interconnected power system shown in **Figure 7**, the IEEE 6 bus reliability test system is reduced to simple delta connection, where it has two nodes of generating units and one node for load. The reduced reliability network is shown in **Figure 9**. Using the methodology explained above, equivalent λ and μ are obtained between generator nodes 1 and 2 and load node. From this, the probability of average power availability at the load is obtained using Eq. (1). The same procedure is used to find the probability of availability at all load points one by one. The probabilities of average power availability at each load are calculated using series-parallel and star-delta approach and are given in **Table 3**.

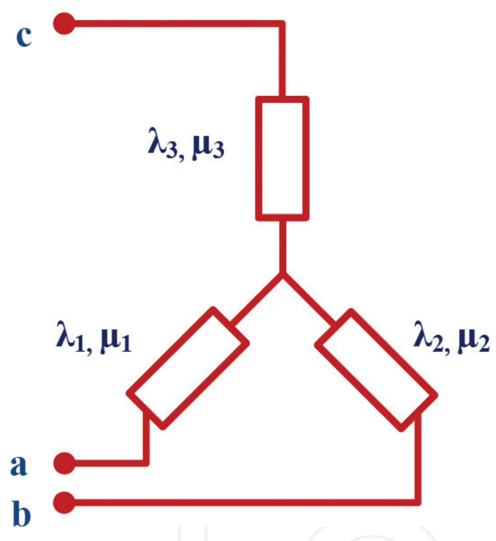

Figure 5. Equivalent star connected reliability model.

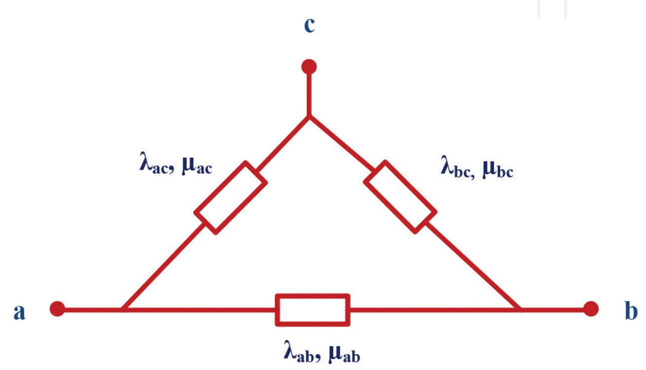

Figure 6. Equivalent delta connected reliability model.

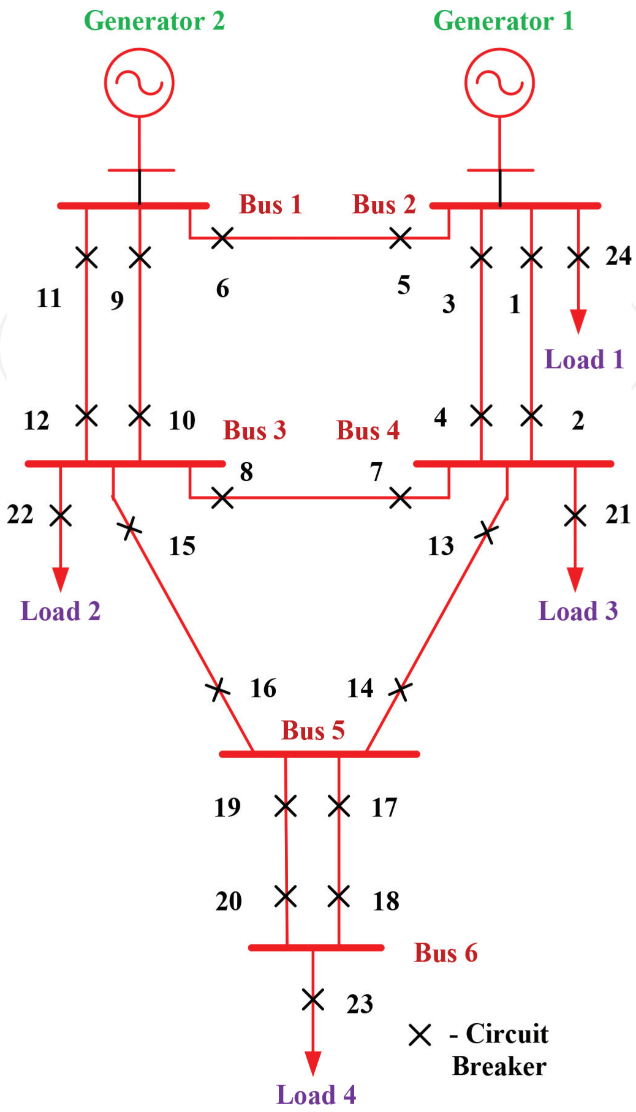

Figure 7. IEEE 6 bus reliability test system.

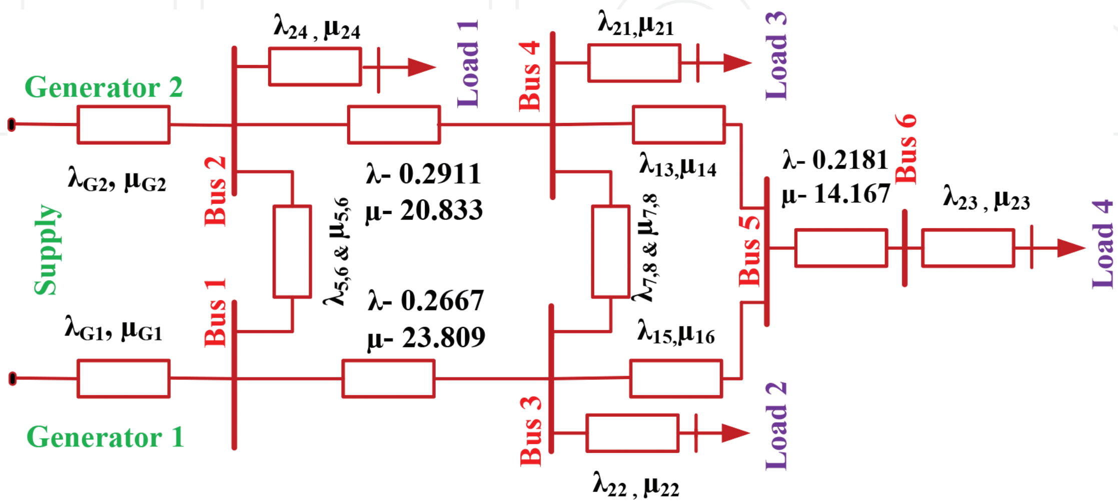

Figure 8. Equivalent reliability model of the IEEE 6 bus reliability test system.

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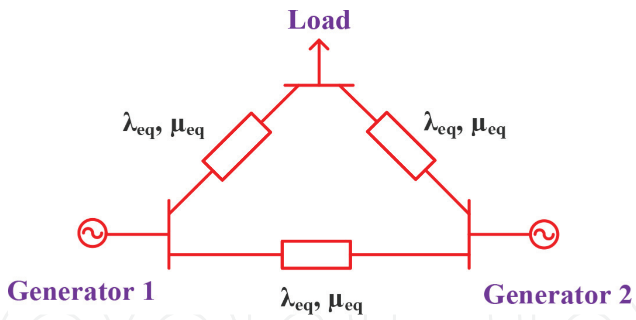

Figure 9. Reduced reliability network.

The evaluation of reliability in the interconnected power system is complex due to the large number of components connected and growing network topology. So far the reliability assessment in interconnected power system is obtained through tracing of the power flow paths [14]. Tracing of paths is time consuming in the case of large networks. Simple and more convenient method based on electrical circuit approach is presented in the following section.

5.4. Node elimination method

The interconnected power system (IEEE 6 bus reliability test system) consists of a number of components, and each component has its own failure and repair rates (λ and μ). From Eqs. (3), (4), (5) and (6), it can be observed the failure rate (λ) is similar to the resistance (R) and the repair rate (μ) is similar to the capacitance (C) in an equivalent electrical network. Hence the reliability model of interconnected power network shown in **Figure 8** can be replaced by an equivalent R-C network for reliability assessment. The classical node elimination method is a known technique. The classical node elimination method is used for power system analysis and has not been used so far for reliability studies. This is the first time the classical node elimination method for reliability assessment in interconnected power system is adapted. It is used to reduce the equivalent electrical network to calculate power availability at load bus.

The equivalent reliability model between generator nodes 1 and 2 and the load bus 4 is shown in **Figure 10**.

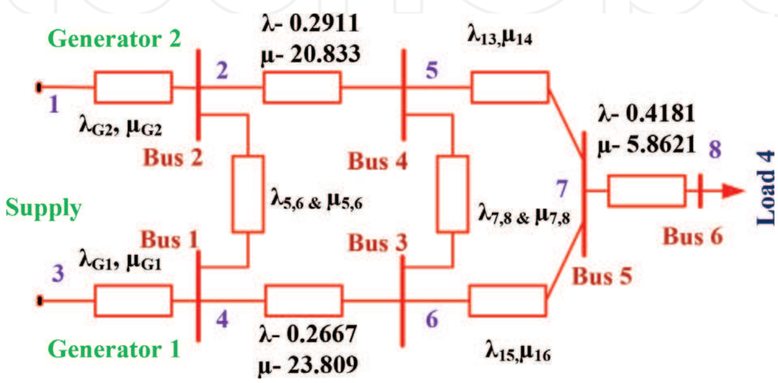

Figure 10. Equivalent reliability model for load 4.

In the analogous electrical model, this network is replaced by two networks where in the first one, all failure rates (λ) in each branch are represented by a resistance (equal to λ) and in the second one each branch is represented by a capacitance equal to μ. For reliability assessment, each of these equivalent electrical networks is reduced to a simplified network connecting the sources to the load nodes where the average power availability is required to be calculated. For simplification of the network, node elimination method is used as explained in the following paragraph.

The power system network consists of eight nodes. The power supply node is considered as a current injection node, and the load node where the availability is to be computed is treated as current sink. This reliability model is used to obtain the power availability at load bus 4 only. The other load nodes do not have any current injection. To reduce the network, the nodes in which the current does not enter or leave are eliminated. The equivalent electrical network is described by the nodal equation.

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ \vdots \\ I_8 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \dots & \dots & Y_{18} \\ Y_{21} & Y_{22} & \dots & \dots & Y_{28} \\ \vdots & \vdots & \dots & \dots & \vdots \\ \vdots & \vdots & \dots & \dots & \vdots \\ Y_{81} & Y_{82} & \dots & \dots & Y_{88} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ \vdots \\ V_8 \end{bmatrix} \tag{19}$$

5.5. Concept of conditional probability

The approach is used to evaluate the power availability in the composite power system, and it is based on conditional probability. A system/component is said to be connected if there exists a path between the source and the sink. The availability of power at the receiving end of a branch not only depends on the failure and repair rates of the components in that branch but also depends on the state of associated components of the branches. These branches can form a power flow path for the particular branch. In the literature, most of the methods are based on the tracing of power flow paths. For example, if a load bus is supplied by three paths a, b and c with power availability at the sending end of each path assumed to P_1, P_2 and P_3 and the probabilities of availability of paths a, b and c are P_a, P_b and P_c, then the probabilities of power unavailable at the ends of paths a, b and c are $(1 - P_1P_a)$, $(1 - P_2P_b)$ and $(1 - P_3P_c)$. Then net probability of average power available (P_L) at the receiving end load bus is given by

$$P_L = 1 - (1 - P_1P_a)(1 - P_2P_b)(1 - P_3P_c) \tag{20}$$

The sending end probabilities of each path are termed as conditional probabilities. The concept of conditional probability is explained with the example given in **Figure 11**. In this directed graph, the generators are connected at the buses 1, 2 and 4. The load buses are 2, 3, 5 and 7. The average power availabilities at the different buses are calculated using the concept of conditional probability as follows.

The availability of power injected into the system by generator G_1 at bus 1 is given by

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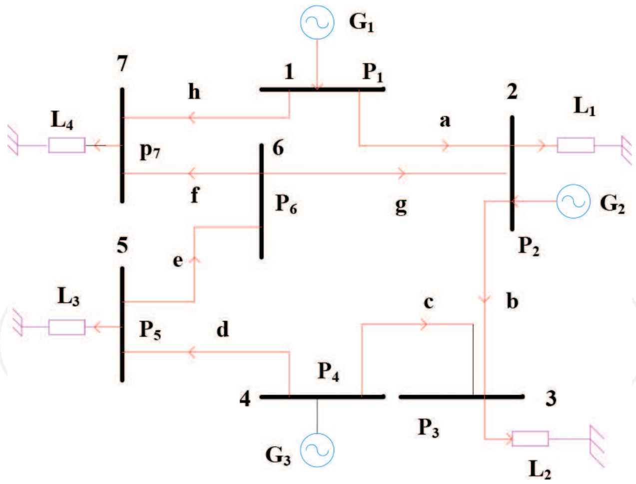

Figure 11. Interconnected power system.

$$P_1 = \frac{\mu_{G1}}{\lambda_{G1} + \mu_{G1}} \tag{21}$$

The incident paths for load L_1 are a and g in addition to path from generator G_2. The branch b is not incident on bus 2. The sending end probability of power availability of path a is P_1 and similarly for path g is P_6 and for generator branch is $\frac{\mu_{G2}}{\lambda_{G2}+\mu_{G2}}$.

So the power availability at bus 2 is given by

$$P_2 = 1 - \left[\left(1 - \frac{\mu_{G2}}{\lambda_{G2} + \mu_{G2}}\right)\left(1 - P_1\frac{\mu_{la}}{\lambda_{la} + \mu_{la}}\right)\left(1 - P_6\frac{\mu_{lg}}{\lambda_{lg} + \mu_{lg}}\right)\right] \tag{22}$$

Similarly the power availability at other buses is given by

$$P_3 = 1 - \left[\left(1 - P_4\frac{\mu_{lb}}{\lambda_{lb} + \mu_{lb}}\right)\left(1 - P_2\frac{\mu_{lc}}{\lambda_{lc} + \mu_{lc}}\right)\right] \tag{23}$$

$$P_4 = \frac{\mu_{G3}}{\lambda_{G3} + \mu_{G3}} \tag{24}$$

$$P_5 = P_4\frac{\mu_{ld}}{\lambda_{ld} + \mu_{ld}} \tag{25}$$

$$P_6 = P_5\frac{\mu_{le}}{\lambda_{le} + \mu_{le}} \tag{26}$$

$$P_7 = 1 - \left[\left(1 - P_6\frac{\mu_{lf}}{\lambda_{lf} + \mu_{lf}}\right)\left(1 - P_1\frac{\mu_{lh}}{\lambda_{lh} + \mu_{lh}}\right)\right] \tag{27}$$

where P_1, P_2, P_3, P_5, P_6 and P_7 are the probability of power available at respective buses; λ_{la}, λ_{lb}, λ_{lc}, λ_{ld}, λ_{le}, λ_{lf}, λ_{lg} and λ_{lh} are the failure rates of the respective branches; and μ_{la}, μ_{lb}, μ_{lc}, μ_{ld},

μ_{le}, μ_{lf}, μ_{lg} and μ_{lh} are the repair rates of the respective branches. Based on the generation availability, the direction of power can change in the network. Similarly another way to calculate the average power availability at the bus 2 is calculated by breaking the branch "b" at bus 2, and new node 2^{I} is created. The power availability at this node is P_2^{I} equal to $P_3\left[\frac{\mu_b}{\mu_b+\lambda_b}\right]$. The new power availability at bus 2, when the branch "b" terminates on bus 2, is given by

$$P_2^{II} = 1 - \left(1 - P_2^{I}\right)(1 - P_2) \tag{28}$$

Knowing the probability of power availability at generators using their respective failure and repair rates, the probability of power availability at all load buses can be computed.

The matrix Y_{Bus} in the above Eq. (19) is the nodal admittance matrix using the concept of conditional probability, and I and V are the fictitious nodal injected current vector and voltage vector of the equivalent R-C network. To evaluate the equivalent failure rate, the nodal Y_{Bus} is made up of only the resistive component (λ) for each element, and for equivalent repair rate, the capacitance component (μ) is used for each element. From the equivalent reliability model shown in **Figure 10**, it is clear that currents I_1, I_3 and I_8 are injected currents and remaining currents are made zero for eliminating the corresponding nodes in the reduced network. Hence the name of this method is called node elimination method. Then Eq. (19) becomes as

$$\begin{bmatrix} I_A \\ I_B \end{bmatrix} = \begin{bmatrix} X & Y \\ Y^T & Z \end{bmatrix} \begin{bmatrix} V_A \\ V_B \end{bmatrix} \tag{29}$$

In Eq. (29), I_A is a vector containing the currents that are injected (I_1, I_3, I_8), I_B vector is a null vector (I_2, I_4, I_5, I_6, I_7), V_A is a vector containing the voltages at the injected currents (V_1, V_3, V_8), V_B is a vector of null vector (V_2, V_4, V_5, V_6, V_7) and Y_{Bus} is formed by the combination of matrices X, Y and Z.

From Eq. (29) the following variables are derived as.

$$\mathrm{I_A = XV_A + YV_B} \tag{30}$$

$$\mathrm{0 = I_B = Y^T V_A + ZV_B}$$

$$\mathrm{V_B = -Z^{-1} Y^T V_A}$$

$$I_A = \left(X - Z^{-1} Y^T V_A\right) V_A \tag{31}$$

The reduced Y_{Bus} is given in Eq. (32), and with the help of this reduced Y_{Bus} matrix, we can draw the simple equivalent delta network as shown in **Figure 9**.

$$Y_{Bus}^{Reduced} = \left(X - Z^{-1} Y^T V_A\right) \tag{32}$$

From the above Eq. (32), the equivalent λ and μ between the source node and the load node are obtained. The reduced Y_{Bus} indicates the nodal equation of the simplified delta network shown

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in **Figure 9**. The equivalent failure and repair rates are obtained from the reduced Y_{Bus} one at a time by assuming λ as resistance R and μ as capacitance C. Since the generator failure and repair rates are already considered in the Y_{Bus} formation, the nodes 1 and 2 of generators in the equivalent reliability model of the network shown in **Figure 9** have 1.0 availability and so can be combined together to evaluate the average availability of power at the load node. So the corresponding network elements between generator 1, generator 2 and load will be in parallel, and overall equivalent λ and μ are calculated. The same procedure is used if there are more than two generators in the power system network. The average power availability at the remaining load points is calculated by adapting the same procedure. The results obtained from this method are given in **Table 1**.

5.6. Modified minimal cut set algorithm

As discussed in previous sections, the composite power system reliability assessment becomes difficult in complex network because of the large number of equipment, components and integration of renewable power generation. Hence the calculation average power availability becomes complex in the modern power system. For power system reliability assessment, usually component failures are assumed to be independent, and reliability indices are calculated using traditional methods like series-parallel and star-delta equivalents of network connections. This section discusses one new evaluation algorithm for the estimation of average power availability based on modified minimal cut set method using conditional probability.

Due to the rapid growth in the power demand, environmental constraints and the competitive power market scenario, the transmission and distribution systems are frequently being operated under heavily loaded conditions, which tend to make the system less stable. The recent literature indicates that most of the blackouts took place due to overloaded transmission system. Further failure of components in the power system causes supply interruptions to connected loads. Statistically, the majority of the service interruptions are happening due to lack of proper planning and operation of power system [15–18]. Therefore complete reliability assessment in transmission and distribution systems (composite power system) is needed in planning of power system. For the above-stated reasons, there is a need for the reliability assessment of composite power systems. One of the objectives used for the evaluation of

S. no.	Cut set	Components in cut
1.	1	C
2.	2	a, b
3.	3	a, c
4.	4	a, b, c
5.	5	a, c

Table 1. Available cut sets.

composite power system reliability is power availability at load buses. Some assumptions made in the proposed algorithms are given below.

1. The failure and repair rates during the operating life of the component are assumed to be constants, and the probability distribution of the failure and repair states of the component is exponentially distributed.
2. Each component repair and failure rate is independent of the states of other components.

In literature there are several methods available for the calculation of network reliability. Monte Carlo simulation method has been used by many authors for the estimation of reliability indices including power availability. This method is very popular but takes large computational time. However, it is widely used for the testing of the new methods.

The proposed algorithm discussed in this chapter has the following advantages:

1. It is very efficient and easy to program.
2. The power availability at each bus can be computed easily without reducing actual network.
3. The proposed algorithm is applicable to any number of bus systems.
4. It takes less computation time compared to other methods.

The results obtained by the proposed step-by-step methods are validated by Monte Carlo simulation and also by classical node elimination method discussed in this chapter [64]. The steps for the methodology used in the proposed method are discussed in the following sections and are applied on practical example in [16]. Some of the relevant work regarding the reliability assessment of complex networks is available in [17, 18].

5.7. Introduction to minimal cut set method

The composite power system reliability assessment is generally based on minimal path or cut enumeration, tracing of power flow paths from which the related reliability indices are calculated. The minimal cut set is a popular method in the reliability assessment for simple and complex configurations. There are several methods available for the calculation of average power availability, which is one of the important reliability indices. Some of the popular methods used are minimal cut set, series-parallel, star-delta, tracing of power flow paths, node elimination method and step-by-step algorithm using conditional probability. Yong Liu et al. [13] have assumed that all the branches included in each cut set of order 1 are assumed to be in parallel, with the sending end of each branch in the cut set having the same probability of power availability which is not correct. This assumption is not used in the proposed method. The procedure adapted is explained in the following sections. The initial step in the cut set method is to figure out the minimal cut sets of the system. The identification of minimal cuts becomes more difficult in large complex systems. Some algorithms like node elimination method presented in [15] can be used to reduce this effort for identification. A step-by-step

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procedure for a modified minimal cut set method is explained in the following sections using IEEE 6 bus, 14 bus and single-area IEEE RTS-96 system.

A system is said to be connected if there exists a path between the source (generator) and the sink (load). The removal of the cut set results in the separation of the system into two independent subsystems. One contains all generator nodes and the other system contains all load nodes. A cut set is a set of components or equipments whose failure will cause system failure [55–60]. The general cut set method is given in the following simple example where the cut sets for load in **Figure 12** are given in **Table 1**.

The definition of a minimal cut set as a cut set in which there is no other subset of components or equipments whose failure alone will cause the system to fail, implies that a normal cut set corresponds to more component failures than are required to cause system failure. The available minimal cut sets for the load in the given example are shown in **Table 2**. The order of the cut set is shown in **Figure 13**.

The concept of conditional probability is explained with the example given in **Figure 12**. In this system the generator is connected at the left side. The load bus is 3. The second-order cut set is supplied by two paths and has sending end power availability of P_1. The equivalent system is shown in **Figure 14**. λ and μ are the overall equivalent failure and repair rates of branches a and b in parallel and in series with branch c.

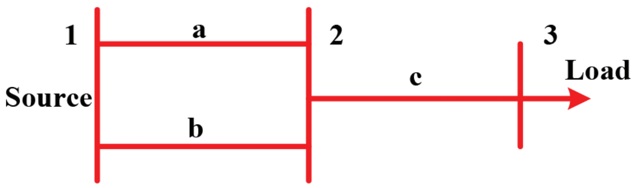

Figure 12. Simple power system to illustrate the concept of cut set.

S. no.	Cut set	Components in cut
1.	1	C
2.	2	a, b

Table 2. Minimal cut sets.

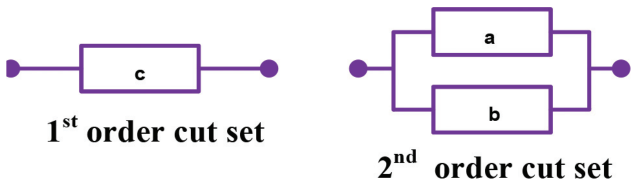

Figure 13. Minimal cut sets for example system.

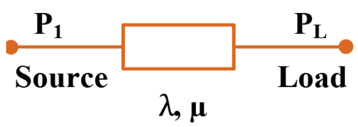

Figure 14. Cut set branch.

Considering the probability of power availability at the source end, the equivalent failure, repair rates between source and load are given by

$$\lambda' = \frac{\lambda}{P_1} \tag{33}$$

$$\frac{1}{\mu'} = (1 - P_1)\frac{1}{\lambda} + \frac{P_1}{\mu}$$

$$\mu' = \frac{\lambda \times \mu}{(1 - P_1)\mu + P_1\lambda} \tag{34}$$

The net average power availability at the receiving end is given by

$$Average\ power\ availability = \frac{\mu'}{\mu' + \lambda'} \tag{35}$$

The proposed technique is used to find the average power availability at the consumer end in a composite power system and is based on the minimal cut sets.

The steps involved in the proposed algorithm are:

1. Draw the graph of the network.
2. Generators are connected to the network node through a branch toward that node.
3. Loads are directly connected to the bus called the load node.
4. All branches are represented by the reliability parameters failure and repair rates (λ and μ).
5. Choose a particular load node.

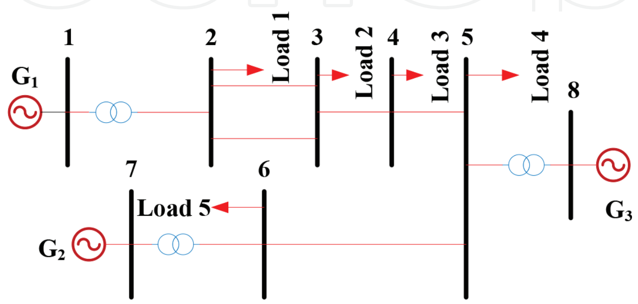

Figure 15. Practical example.

6. Obtain the cut set which isolates this node.
7. For those cut branches which are incident in this node, assume the probability of availability of power at the node at the other end of the branch.
8. Based on these probabilities (P), compute the probability of average power availability at the chosen load node.
9. Find the cut set which isolates all these above nodes identified in step 7.
10. Repeat steps 7 and 8 to find the power availabilities at these nodes assuming the probabilities at the other end of the branches in the cut set.
11. Using these probabilities, evaluate the probability of power availabilities at these cut nodes.
12. Repeat this exercise until all the nodes are covered including all generator nodes.
13. Using these probabilities works backwards to compute the probability of power availability at the chosen load node.
14. Repeat this exercise for all the load nodes.
15. Obtain the system overall average power availability from step 14.

The proposed algorithm is tested with the practical example taken from the Roy Billinton paper. The configuration of the practical example is shown in **Figure 15**. The system is connected to generators at the buses 1, 7 and 8 through interconnecting transformers. The failure and repair rates are assumed to be identical for all components throughout the system. This is only for convenience. If different failure and repair rates are specified for each component like generator, transformer, line, etc., the same can be used. There will be no change in the procedure steps 1 to 15 described above.

6. Results and discussions

The algorithms/methods presented in this chapter have been applied to practical example. In this practical example, all components are assumed to have identical reliability data ($\lambda = 0.1$; $\mu = 10$). The results are shown in **Table 3**. The proposed methodology is validated by the Monte Carlo simulation method, node elimination method [15] and step-by-step algorithm using conditional probability [16]. The algorithm developed in this chapter is also applied on IEEE suggested power system network to validate the results. The IEEE 6 bus reliability test system is shown in [15]. The reliability data of the system is given in [15]. The average power availability at the load buses is given in **Table 4**. To show the efficiency of the proposed method for reliability assessment of large systems, the IEEE 14 bus system and IEEE RTS-96 system are used. The IEEE 14 bus system is shown in [64]. The reliability data of the IEEE 14

S. no.	Load no.	Modified minimal cut set method	Node elimination method	Monte Carlo method	Step-by-step algorithm using conditional probability
1	Load 1	0.994	0.999	0.989	0.999
2	Load 2	0.984	0.985	0.974	0.992
3	Load 3	0.985	0.995	0.956	0.995
4	Load 4	0.991	0.998	0.985	0.998
5	Load 5	0.988	0.998	0.965	0.998

Table 3. Average power availability in practical example.

S. no.	Load no.	Modified minimal cut set method	Node elimination method	Monte Carlo method	Step-by-step algorithm using conditional probability
1	Load 1	0.994	0.994	0.92737	0.990
2	Load 2	0.964	0.967	0.89847	0.968
3	Load 3	0.935	0.939	0.90790	0.936
4	Load 4	0.883	0.884	0.85934	0.887

Table 4. Average power availability in IEEE 6 bus system.

S. no.	Load no.	Modified minimal cut set method	Node elimination method	Step-by-step algorithm using conditional probability
1	Load 1	0.956	0.967	0.967
2	Load 2	0.965	0.967	0.966
3	Load 3	0.967	0.967	0.966
4	Load 4	0.933	0.938	0.933
5	Load 5	0.911	0.914	0.914
6	Load 6	0.911	0.917	0.917
7	Load 7	0.942	0.951	0.950
8	Load 8	0.933	0.939	0.939

Table 5. Average power availability at different loads in IEEE 14 bus system.

bus system is given in [15]. The results obtained for the IEEE 14 bus system are shown in **Table 5**.

The proposed modified minimal cut set algorithm is also applied and tested on IEEE single-area RTS-96 system shown in [15]. The reliability data for IEEE single-area RTS-96 system is taken from [15]. The average power availability at the load buses for the system is shown in **Table 6**.

S. no.	Load no.	Modified minimal cut set method	Node elimination method	Step-by-step algorithm using conditional probability
1	Load 1	0.881	0.885	0.885
2	Load 2	0.822	0.819	0.812
3	Load 3	0.555	0.558	0.555
4	Load 4	0.852	0.846	0.852
5	Load 5	0.812	0.812	0.812
6	Load 6	0.813	0.812	0.813
7	Load 7	0.815	0.812	0.813
8	Load 8	0.833	0.836	0.833
9	Load 9	0.855	0.859	0.859
10	Load 10	0.854	0.857	0.854
11	Load 11	0.811	0.818	0.811
12	Load 12	0.836	0.832	0.836
13	Load 13	0.844	0.845	0.844
14	Load 14	0.786	0.788	0.788
15	Load 15	0.764	0.763	0.764
16	Load 16	0.862	0.868	0.864
17	Load 17	0.800	0.808	0.800

Table 6. Average power availability at different loads in IEEE single-area RTS-96 system.

7. Conclusions

In this chapter reliability modeling of power system components is analyzed by the node elimination method and modified minimal cut set method. The IEEE 6 bus system, IEEE 14 bus systems and single-area IEEE RTS-96 system are used to evaluate the reliability. The two methods gave similar results on average power availability at load bus. The series-parallel and star-delta method is quite difficult for the reduction of complex networks, whereas the node elimination method is easy even for large systems. The new methodologies proposed in this chapter are very useful for power system planners and utility consumers. The electrical circuit approach method is further useful to the power system operators to make decision on the future average power availability. The proposed method on minimal cut set is useful for the reliability assessment in the planning and operation of larger power system network.

Conflict of interest

There is no potential conflict of interest.

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