Chapter 34
Uninterruptible Power Supply System Configuration Reliability Studies

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Abstract The purpose of this paper is to predict the reliability parameters of the DC uninterruptible power supply (UPS) by using the reliability block diagram (RBD) method. Application of RBD in predicting reliability of the DC UPS is capable to produce the important quantitative reliability indices such as the system's failure rates, mean time between failures (MTBF), availability, and unavailability, which will be useful to the UPS designer, manufacturer and finally the user to decide for the best DC UPS configurations. In this paper, two configurations of the DC UPS (with and without generator) are considered, and comparisons on their resultant reliability parameters by using the proposed RBD method are discussed in detail. Sensitivity analysis on the major components of the DC UPS is performed to investigate the effect on the overall reliability of the power systems. Field data from industrial best practice are used to validate the results of the analytical model.

Keywords Uninterruptible power supply · Reliability block diagram · Mean time between failures

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34.1 Introduction

Most electrical installations require uninterruptible power, virtually free of frequency excursions and voltage dips, surges and transients. Reliability demands become much more important, especially under emergency conditions such as natural catastrophes and accidents in which a public power failure is likely to happen [1].

Conventionally, reliability parameters of the DC uninterruptible power systems are presented by using the state-space method [2]. In this approach, firstly, all the possible system states have to be identified. Then, the state-transition diagram has to be constructed in order to show the interdependencies between the states. The system states probabilities and the inter-state transition rates (from state i to j) have to be determined. The simulation result suggested that the reliability indices improve considerably with increase in battery discharge time. The results agreed that a standby generator should be considered if high reliability of critical DC load supply is required. The difficulty in constructing the state-transition diagram for the redundant and bigger system has made the method become less popular as a method in determining the standby power system's reliability. Furthermore, the inter-state transition rates are quite complicated to identify.

A study by [3] proposed the minimal cut set method. This method is very similar to the state-space approach where the state-transition diagram has to be constructed, and the inter-state transition rates and the steady-state probabilities have to determine first. The failure rates of some major components used for this simulation also being applied in this paper. The author suggested that the reliability of DC UPS could be improved by a generator and by introducing accelerated maintenance. Again, the difficulty in constructing the state-transition diagram of the overall system has made this method less preferable in determining the reliability indices of power systems.

Papers [4, 5] describe the methodology to analyse the availability and reliability performance of the DC uninterruptible power supply (UPS) based on Markov chains. A typical telecom DC UPS system is taken into consideration in this paper. The results obtained were useful as the reliability parameters of each major component can be achieved individually, and the outcomes of the overall system can be compared easily. However, to construct the system's Markov graphs, a great understanding of the system operations is essential. Like the other two methods before, this method is less likely to be used in the UPS reliability analysis.

Due to the difficulty and complicatedness in constructing the model for the uninterruptible power systems, UPS manufacturers rely on the existing field data [6, 7]. The method consists of tracking a sample population of a product and gathering the failure data. With this data, the failure rate and MTBF can be calculated.

This paper proposed the reliability block diagram (RBD) method for predicting the failure rates (λ), mean time between failure (MTBF), availability (A), and unavailability (W) for the two types of DC UPS configurations, with and without generator. Reliability indices of the major components that made up the DC UPS are considered. Finally, comparisons between the DC UPS will be made by considering the overall system's reliability.

The RBD method is widely used in software engineering. It is found to be very popular in determining the reliability of the computer networking systems and in the telecommunication network industry. However, this method is never being applied in predicting reliability parameters in power engineering studies. The RBD for the electrical power system is usually difficult to prepare, and in some cases, a unique diagram may not exist.

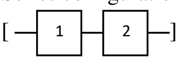
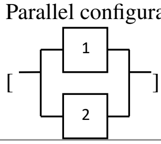
The advantages of using the RBD method to estimate the reliability parameters of the UPS system manifested in several ways:

1. Simple to construct the reliability model as it is quite close to the system single-line diagram/layout.
2. RBD modelling require less component's input data compared to all other method to obtain reliability indices.
3. RBD model can clearly show the interdependencies of the components in the system as they will be arranged in series or parallel between the system input and output nodes.
4. As the model is quite similar to the single-line diagram of the system, a thorough understanding of the system's working operation is not essential as the user can always refer to the single-line diagram.
5. Every components input data are treated independently. Thus, it is possible to perform a sensitivity analysis of every component in the system to investigate 'its effect on the overall system.

34.2 Reliability Block Diagram (RBD) Method

In the RBD method, the UPS reliability model must be build first, and a failure rate, λ (failures/h) must be assigned to each block. From the system's single-line diagrams, the resultant reliability model will be constructed [8]. For simplicity, in this UPS reliability modelling, the major components were assumed to be connected either in series or parallel, as shown in Table 34.1. For the overall system's unavailability calculations, the unavailability (W) and repair rate (μ) of each component are

Table 34.1 Component failure rates and unavailability equation

Series configuration 	Parallel configuration 
Failure rates, $\lambda_S = \lambda_1 + \lambda_2$ (34.2)	Failure rates, $\lambda_P = \underline{\lambda_1, \lambda_2}$ (34.4)
Unavailability, $W_S = W_1 \exp(-\mu_1.T) + W_2 \exp(-\mu_2.T)$ (34.3)	$\lambda_1 + \lambda_2$
	Unavailability, $W_P = W_1 \exp(-\mu_1.T), W_2 \exp(-\mu_2.T)$ (34.5)

required. The battery reserve time, T is also needed in the calculation. The equations for failure rates and unavailability in series and parallel configurations are presented by Eqs. 34.1–34.4.

34.2.1 DC UPS system—With Generator

In this DC UPS system, the rectifier will receive its input AC power either from utility or the generator unit. Figure 34.1 shows the single-line diagram of the DC UPS system with generator [9]. Under normal operation, the utility power will supply AC power to the rectifier through the mechanical static switch. Rectifier will convert the AC supply to DC supply in order to feed to the critical DC loads. At the same time, the DC output from rectifier will flow to the battery charger to charge the battery system. In the event of utility power failure, there is no AC power supplied to the rectifier. As the battery system is connected to the critical load bus, the battery will be discharged to supply DC power to the DC loads. At the meantime, the generator set is ready to start and supplying the AC power to the rectifier. The generator will need some time (few minutes) to initialize before supplying AC power. For this reason, a battery system is needed to cater during the generator initialising time. The reliability model that has been built by the system configuration diagram is presented in Fig. 34.2, which comprises two parallel-connected blocks, block 1 and block 2.

After the reliability model has been constructed, the failure rate and unavailability of the UPS system can be calculated using (Eqs. 34.1–34.4) in Table 34.1. In this paper, for simplicity, the battery reserve time, T of 1 h is considered for both UPS configurations. The models for the failure rate and unavailability measurements of the UPS system are presented in Table 34.2.

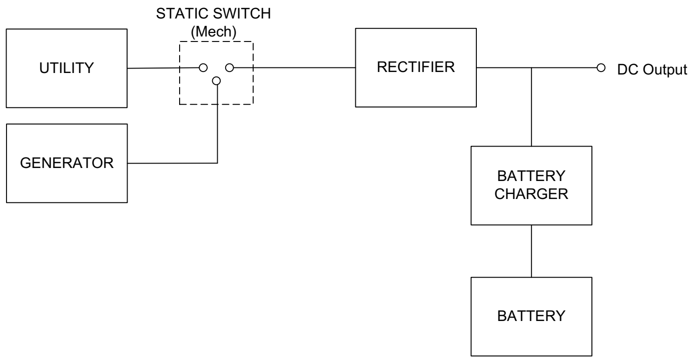


Fig. 34.1 DC UPS (with generator)—system configuration

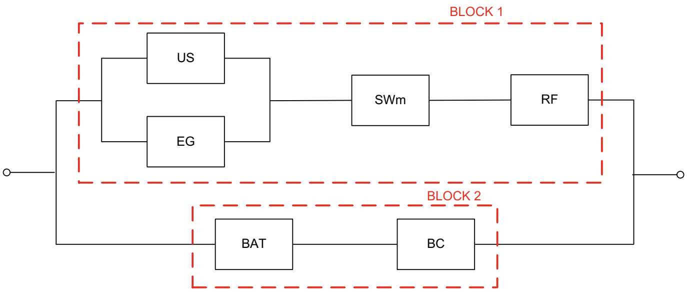


Fig. 34.2 DC UPS (with generator)—reliability model

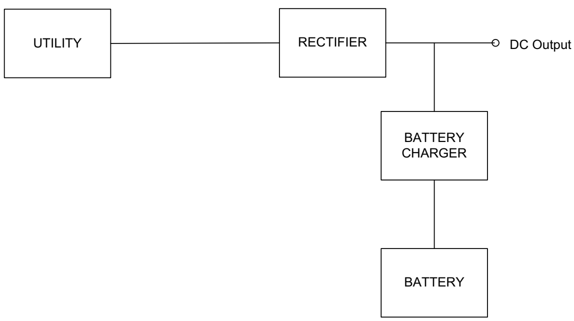
Table 34.2 Failure rates and unavailability calculations for DC UPS with generator

Failure rate calculation	Unavailability calculation
$\frac{1}{\lambda_1} = \frac{1}{\lambda_{US}} + \frac{1}{\lambda_{EG}}$ $\lambda_1 = \frac{\lambda_{US} \cdot \lambda_{EG}}{\lambda_{US} + \lambda_{EG}}$	$W = W_1 + W_2 = \left[\begin{array}{l} W_{US/EG} \cdot \exp(-\mu_{US/EG} \cdot \mathrm{T}) \\ + W_{SWm} \cdot \exp(-\mu_{SWm} \cdot T) + \\ W_{RF} \cdot \exp(-\mu_{RF} \cdot T) \end{array} \right]$ $+ \ [(W_{US/EG} + W_{SWm} + W_{RF}] \cdot [W_{BAT} + W_{BC}]$
$\lambda_2 = \lambda_1 + \lambda_{SWm} + \lambda_{RF}$	
$\lambda_3 = \lambda_{BAT} + \lambda_{BC}$	
$\lambda_T = \frac{\lambda_2 \cdot \lambda_3}{\lambda_2 + \lambda_3}$	

34.2.2 DC UPS System—Without Generator

This is the most basic configuration of the DC UPS system [9]. From the system configuration in Fig. 34.3, it is shown that under the utility failure condition, the back-up time depends solely on the battery system. Once the utility power resumed, the rectifier will feed DC supply to the critical DC loads and charge the battery. The reliability model in Fig. 34.4 confirms that the critical load will only be supplied by either the utility or the battery supply.

Fig. 34.3 DC UPS (without generator)—system configuration



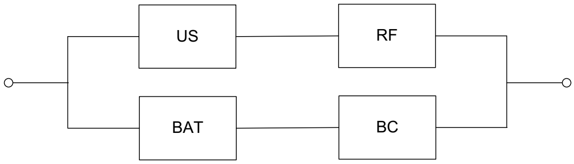


Fig. 34.4 DC UPS (without generator)—reliability model

34.3 Results and Discussion

Table 34.4 shows the reliability values of the major components for the UPS being studied indicating the values for failure rate (λ), unavailability (W), and repair rate (μ) [1, 3, 10]. Table 34.3 shows how the failure rate and unavailability of the UPS system were modelled by using the RBD modelling method.

Three major indicators for UPS system reliability were considered here. Unavailability (W) is defined as the inability that an entity is not in a state to perform a required function, under a given conditions, at a given instant of time [1]. Failure rate (λ) is the probability that an entity loses its ability to accomplish a function during the interval [t, t + dt], knowing that it is not failed between [0, t]. The mean

Table 34.3 Failure rates—unavailability calculations for DC UPS without generator

Failure rate calculation	Unavailability calculation
$\lambda_1 = \lambda_{\mathrm{US}} + \lambda_{\mathrm{RF}}$	$W_{DC2} = \left[W_{\mathrm{US}} . \exp(-\mu_{\mathrm{US}} \cdot T) + W_{\mathrm{RF}} . \exp(-\mu_{RF} \cdot T) \right] + [(W_{\mathrm{US}} + W_{\mathrm{RF}}] \cdot [W_{\mathrm{BAT}} + W_{\mathrm{BC}}]$
$\lambda_2 = \lambda_{\mathrm{BAT}} + \lambda_{\mathrm{BC}}$	
$\frac{1}{\lambda_T} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$ $\lambda_T = \frac{\lambda_1 \cdot \lambda_2}{\lambda_1 + \lambda_2}$	

Table 34.4 Reliability data used for the reliability block diagram modelling

Component	Unavailability W	Failure rate, λ (failures/h)	Repair rate, μ (h)
Utility	1.08E–5	1.0000E–3	0.232
Generator	6.30E–6	3.6597E–6	0.054
Utility/gen (US/EG)	6.80E–8	1.5000E–7	2.2
Bypass switch, SWm	1.50E–6	1.0000E–5	0.5
Rectifier	4.60E–8	4.3478E–6	0.5
Battery charger	4.60E–8	4.3478E–6	0.5
Batteries	3.90E–6	1.6393E–7	0.042

Table 34.5 Results from reliability block diagram modelling

	Unavailability, W	Failure rate, λ	MTBF (h)	MTBF(y)
DC UPS with generator	9.452E–7	3.432E–6	2.913E–5	31.65
DC UPS without generator	8.592E–6	4.492E–6	2.226E–5	25.42

time between failures (MTBF) is the expected operating time between two failures [1]. MTBF is the reciprocal of failure rate (i.e. MTBF = 1/λ)

34.3.1 DC UPS MTBF Comparison

The result in Table 34.5 shows that DC UPS with a generator will give higher MTBF value. The generator will provide another path of the back-up power supply in the event of utility power failure. Furthermore, the battery system will not be "deep-discharged" during power failure as the critical loads only on-battery for a short time (i.e. initialising time of generator). The failure rate of DC UPS with generator is lower compared to the system without generator. The failure rate of the generator is found to be low enough to affect the overall system failure rates. The unavailability of the system without generator is lower, and this can suggest that inclusion of generator unit in the DC UPS configuration can increase the availability of the overall system.

34.3.2 Battery Back-Up Time (T)

By increasing the battery reserve or back-up time, T the unavailability of the DC UPS will be reduced, as shown in Fig. 34.5. The slope of the two straight lines obtained for both DC UPS configurations, clearly shows that DC UPS with generator unavailability will reduced in faster rate compared with the DC UPS system without generator. For the DC UPS without generator, during the mains failure, the input power to the critical loads depends solely on to the battery supply and the battery supply depends on the battery's back-up or reserve time. For the DC UPS with generator, during mains failure, the critical loads will mainly receive input supply from generator. The load will only take power from battery system during the initialising of the generator unit.

34.3.3 Sensitivity Analysis of DC UPS MTBF

Sensitivity analysis was performed to investigate the effect of varying the MTBF of major components in the DC UPS on the overall reliability of the power systems.

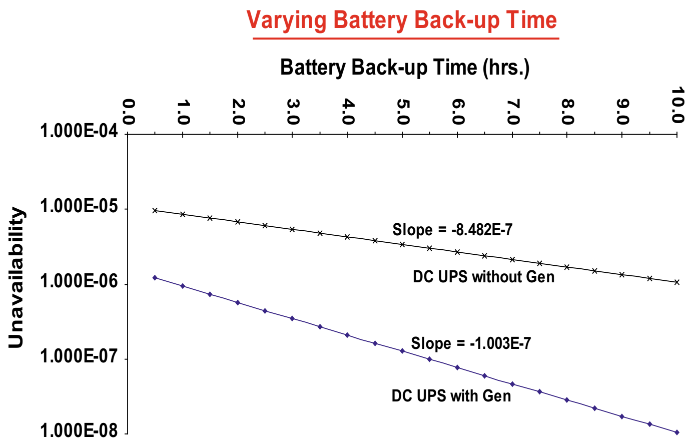


Fig. 34.5 Varying battery back-up time on DC UPS unavailability

The sensitivity analysis was done by increasing the components' MTBF value, and the effect of this value to the overall system MTBF was indicated by the slope of the graph obtained.

By varying the utility MTBF, from Fig. 34.6, the result suggested that for the DC UPS without generator, there is a high dependability on the utility's MTBF. Utility's MTBF has a very small effect on the MTBF of DC UPS with generator. Figure 34.7 shows that for DC UPS with generator the rectifier MTBF has a significant effect on the overall system MTBF. Higher rectifier MTBF will result in an improved system MTBF. For the DC UPS without generator, an increase in the rectifier MTBF has no effect on the overall system MTBF.

By varying the battery MTBF, from Fig. 34.8, both DC UPS produced almost the same curve. The DC UPS with generator has a higher system's MTBF compared

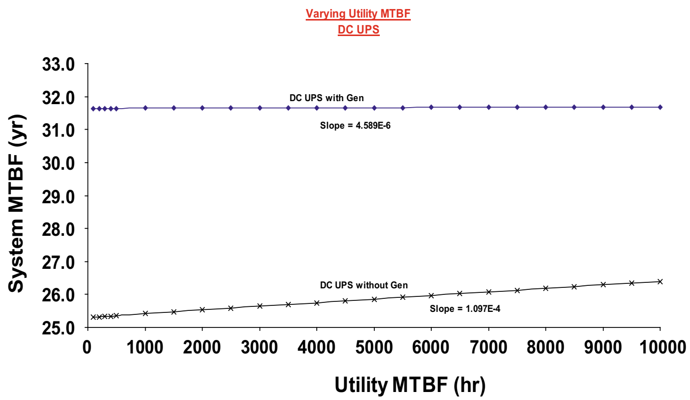


Fig. 34.6 Varying utility MTBF on DC UPS system MTBF

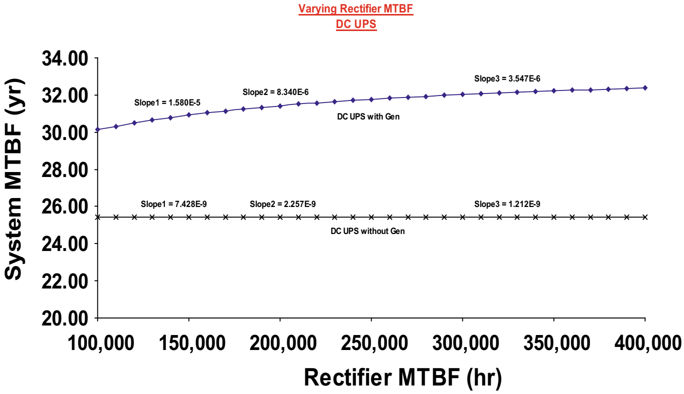


Fig. 34.7 Varying rectifier MTBF on DC UPS system MTBF

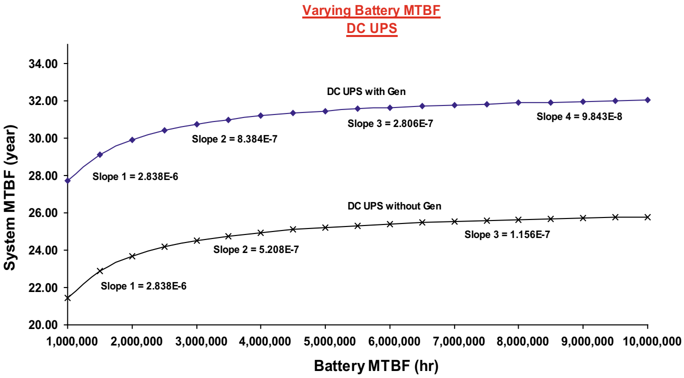


Fig. 34.8 Varying battery MTBF on DC UPS system MTBF

to the one without generator. It was clearly shown in the graph that for both DC UPS configurations, for lower battery MTBF values (i.e. less than 6,000,000 h), the system MTBF increases with the increase in battery MTBF. The almost horizontal line on the curve for the higher value of battery MTBF (i.e. greater than 6,000,000 h), suggested that the increment in battery MTBF values have no effect on the overall system MTBF.

Figure 34.9 shows the two straight lines with the same slope for both DC UPS systems. Similarly, the DC UPS with generator will give a better system MTBF value compared to the DC UPS without generator. The graph also suggested that the system MTBF is highly dependent on the battery charger MTBF. The result also suggested that the battery charger module is the most important component in the system to ensure its reliability. During the normal operation of the UPS, battery charger will float charge the battery, and during power failure, battery charger will be the link between the battery supply and the critical load.

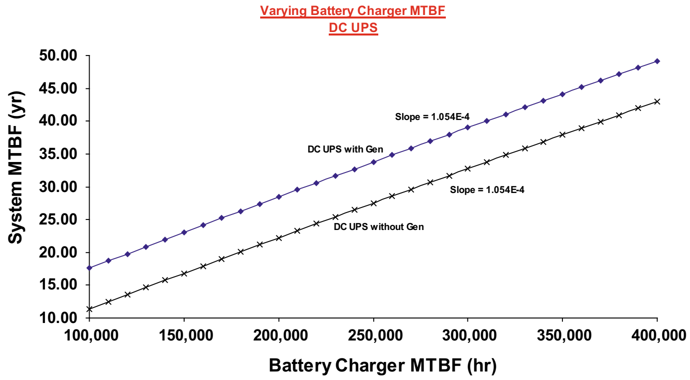


Fig. 34.9 Varying battery charger MTBF on DC UPS system MTBF

By varying the generator MTBF up till 200,000 h, it was found that the system MTBF increases greatly. However, for the higher value of generator MTBF, the system MTBF increment became less significant, as shown in Fig. 34.10. As discussed earlier, the purpose of static switch is to transfer the input supply from the utility to generator supply during mains failure. Figure 34.11 shows that as the static switch MTBF increases, the system MTBF also increase. In other words, the system MTBF depends greatly on static switch MTBF and higher value of static switch MTBF will result a high system MTBF.

Table 34.6 shows how the MTBF values of the major components in UPS system being rated with respect to its effect on the overall system's MTBF values. Low rating means less effect and high rating means highly dependable to the system MTBF. The sensitivity analysis study suggested that in order to achieve a higher DC UPS with generator reliability, the battery charger reliability has to be improved. As for the DC

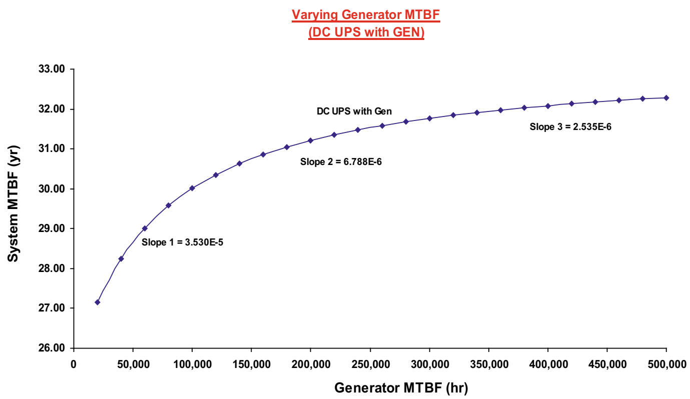


Fig. 34.10 Varying generator MTBF on DC UPS system MTBF

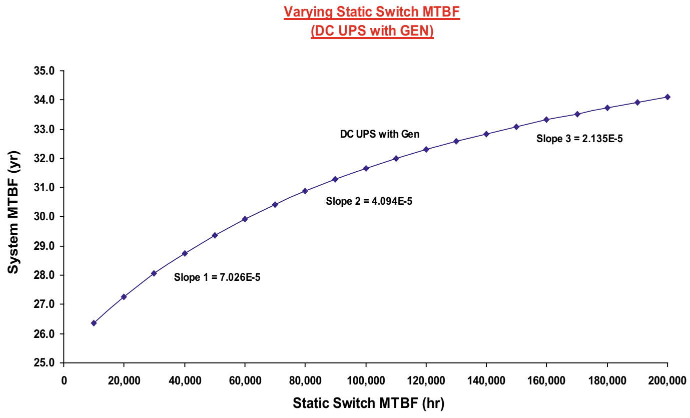


Fig. 34.11 Varying static switch MTBF on DC UPS system MTBF

Table 34.6 Rating on determining factors on overall UPS system's MTBF value

UPS configuration	Determining factors (on system MTBF)	Rating
DC UPS (with generator)	Utility	Low
	Generator	Low
	Static switch	Medium
	Rectifier	Low
	DC battery	Low
	Battery charger	High
DC UPS (without generator)	Utility	High
	Rectifier	Low
	DC battery	Low
	Battery charger	High

UPS without generator, the overall system's reliability will increase when the utility and the battery charger reliabilities increase.

34.3.4 Probability of Failures

The failure rates (λ) of each UPS configuration can be used to calculate the reliability and the probability of failure of a system with respect to time (t), using the equation:

$$\text{Reliability, } R = \exp^{-\lambda \cdot t} \tag{34.1}$$

Table 34.7 Probability of failures

DC UPS configuration	*R* (1 year)	Fail (1 year)	*R* (5 years)	Fail (5 years)
With generator	0.9704	0.0296	0.8604	0.1396
Without generator	0.9614	0.0386	0.8214	0.1786

Table 34.7 shows the reliability, *R* or in a simple terms, the probability of surviving $R(t)$ and the probability of failure Fail(t) of the DC UPS systems. There was a very slight improvement on the probability of failure for the DC UPS with and without generator. The probability of failure to happen with the 5-year period is 13.96% for the DC UPS with generator and 17.86% for the DC UPS without generator.

34.3.5 Unavailability Comparison

Unavailability measures with respect to time per year for both UPS systems are presented in Table 34.8. The DC UPS with generator will be unavailable only for 29.81 s/year, whereas DC UPS without generator will be unavailable for 4.516 min/year.

In order to verify the result obtained by using the RBD method, the actual field data from various UPS companies were used. Table 34.9 shows the availability and MTBF figures for the two types of DC UPS considered. As expected, the results from the RBD method were close to the field data.

Table 34.10 shows that there was a very slight difference between the result obtained from RBD and field data for both availability and MTBF. For availability of the DC UPS with generator, the field data are $3.01 \times 10^{-5}\%$ more than the RBD method. The field data are $1.38 \times 10^{-5}\%$ more than RBD method for availability of DC UPS without generator configuration. In the MTBF results, field data give

Table 34.8 UPS unavailability

	Unavailability			
	%	h/year	min/year	s/year
DC UPS with generator	9.452E–05	0.0083	0.497	29.81
DC UPS without generator	8.592E–04	0.0753	4.516	270.95

Table 34.9 Results verification (RBD vs. field data)

	Calculated (RBD)		Field data	
	availability, *A*	MTBF (h)	availability, *A*	MTBF (h)
DC UPS (with generator)	99.9999054%	2.772E5	99.9999355%	2.600E5
DC UPS (without generator)	99.9991408%	2.226E5	99.9992788%	2.142E5

Table 34.10 Percentage differences between RBD and filed data results

	Availability % difference	MTBF % difference
DC UPS (with generator)	3.010E–5	– 6.61538
DC UPS (without generator)	1.380E–4	– 3.92157

6.62% less value compared to the RBD for the DC UPS with generator and 3.92% less value to RBD for the configuration without generator.

It was observed that for the DC UPS, the inclusion of generator will result:

- Lower failure rates
- Higher mean time between failures
- Increased system's availability
- Reduced unavailability

Performing sensitivity analysis on the major components of both DC UPS configuration clearly shows that the system without generator reliability depends highly on utility power reliability. For the configuration without generator, the battery system will be the only line of defence against the critical load shutdown during utility failure. Thus, the DC supply to the critical loads depends solely on the back-up time of the battery system. However, for the configuration with generator, the battery system will be the secondary back-up power supply (i.e. during the initialising of the generator) as primarily the back-up supply comes from the generator unit.

The sensitivity analysis also highlights the importance of the battery charger reliability on both the DC UPS system's reliability. Improvements in the battery charger's MTBF will result a higher value of overall system's MTBF.

Although the availability and failure rate is certainly attractive for such a simple scheme, the DC system without generator cannot be considered as a viable option for customers with critical loads (essential and vital customers) that require long-back-up time, as this configuration depends solely on-battery system reliability during power outage. Unlike DC UPS with generator, the battery system is used to feed the loads only before the generator has started up.

34.4 Conclusion

This paper proposed the RBD for the reliability analysis of uninterruptible power supplies (UPS). RBD is found to be a simple and effective method to predict the important reliability parameters of UPS systems.

The main advantage of this method is its simplicity in constructing the RBD reliability model compared to other methods. The ability of this method to produce the reliability indices of the overall UPS system allows user to perform a sensitivity analysis to investigate the effect of varying the MTBF of major components in the DC UPS on the overall reliability of the power systems. Eventually, the result obtained can be used to establish the area where improvements have to be made to achieve the highest system reliability.

The major finding from this study is for the critical loads, with a long-back-up time, DC UPS system with generator will be the best option. In terms of the system reliability, it will give a lower failure rates (λ), higher MTBF, and finally better availability (A).

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