EMERGENCY POWER SUPPLY

Utility electric power systems generally supply electric power of acceptable quality. It is, however, reasonable to assume that electric power from a single source will have interruptions that most of the customers can tolerate with some inconvenience but without any significant damage. Yet some customer loads, such as medical facilities, emergency lighting, and data processing and communication centers, cannot tolerate interruptions in electric supply. Loss of power to medical facilities may result in loss of life, interruption of emergency lighting may lead to vandalism, and loss of power to communication and data processing centers can cause similarly serious problems. For such loads, emergency and standby power systems (1,2) are installed to provide electric power of acceptable quality and quantity to critical portions of the user facilities in an event of failure of normal electric supply.

Emergency and standby power systems are independent reserve sources of electric energy that, upon failure of the utility supply, can provide electric power of acceptable quality so that the concerned facilities may continue to operate satisfactorily. The difference between emergency and standby supplies is that the former comes into operation automatically, within a specified time following the failure of the normal supply. The appropriateness of installing an emergency or standby power system at a facility, as well as the configuration of the installed system, is determined by such factors as the criticality of the load, the nature of the load, and the justifiable cost of reliability of the supply required by the load.

The following sections will describe briefly the required reliability concepts, the factors governing the choice and configuration of emergency and standby power systems, the components constituting such systems, and the methods of determining the reliability of such systems.

RELIABILITY ISSUES

In introducing reliability issues, we will first introduce some basic reliability measures that apply to emergency and standby power supplies. For more detailed descriptions of reliability issues, see Refs. 3 through 8.

Load interruption frequency. This is the mean number of interruptions per unit time. A more commonly used name is frequency of system failure.

Failure rate. This is the mean number of failures per unit up time. This may apply to a component or a system. The up time refers to the period of time during which the component or system is functional. For highly reliable systems, this is almost equal to the failure frequency.

Mean interruption time. This is the expected or long term average duration of a single interruption. It is more commonly known as mean down time.

Expected duration of load interruption. This is the average time of interruption during the interval under consideration. It is the product of load interruption frequency and mean interruption time.

Each facility or load has specific requirements in terms of acceptable interruption frequency or duration. For instance, a steel mill is very sensitive to interruption frequencies; a power failure during the processing of a job is likely to cause the jobs wasting and considerable expense. Such a facility requires an emergency power supply that can come into operation almost immediately following failure of the primary supply. On the other hand, a chemical plant may use an electrolytic process that is not affected by frequent interruptions as long as they are brief, and the process continues while it receives energy. For such a plant an offline standby supply is probably adequate. A facility that requires both frequency and duration of power interruptions to be extremely small is a hospital intensive care unit. Such a situation needs a highly reliable uninterruptible power supply.

Higher reliability of supply obviously demands higher cost of installation, and the nature and criticality of the load determine the configuration of the emergency or standby power supply, the amount of reliability built into it, and its location online or offline.

CONSTRUCTING EMERGENCY AND STANDBY POWER SYSTEMS

The equipment used in assembling emergency and standby power systems can be classified as energy sources and energy storage equipment or switching equipment. Some of the commonly used sources and switching equipment will be described briefly here. A more thorough treatment is available in IEEE Standard 446-1987 (1).

Power Sources and Energy Storage Equipment

Generators. Generators used in emergency and standby power systems may be engine driven or turbine driven. Engine driven generators normally use diesel, gasoline, natural gas, or liquefied petroleum gas as fuels. Turbines use steam or gas as prime movers. These generators normally have low startup times (in the order of minutes or seconds) and capacities in the kilowatt to megawatt range. They are generally applied as offline units, and may be used in combination with electrical or mechanical energy storage devices.

Electrical Energy Storage Devices. Batteries are the commonly used electrical energy storage devices. Normally, while commercial (utility) power is available, it is used to charge the battery through a rectifier. Upon failure of the utility supply, the energy stored in the battery is supplied to the critical load through an inverter. An inverter-battery system may be used as an offline supply or it may be kept online, with an appropriate switching device that allows the load to draw power from the battery almost instantaneously following failure of the utility supply. The battery provides power to the load for a limited but known period of time, during which an alternative offline source may be brought into service if the utility supply is not restored within the time the battery power is known to be available.

Mechanical Energy Storage Devices. Such a device generally consists of a rotating flywheel mounted on the connecting shaft of a motor-generator set. This is normally used online, with the motor continuously energized by the utility power, and the load connected to the generator in the motor-generator set. In the event of failure of the utility supply, the energy stored in the rotating flywheel continues to rotate the generator shaft for a few seconds, allowing time for an offline source to be brought into service if necessary. This kind of mechanical energy storage system can be used in combination with other standby systems.

Switching Devices

Switching devices establish or change connections in or among circuits. The switching devices commonly used in emergency and standby power supplies are transfer switches and bypass switches.

Automatic Transfer Switch. This is self-acting equipment for transferring one or more load conductor connections from one power source to another. Automatic transfer switches (ATS) may be mechanical or static (STS). Mechanical switches generally operate within tenths of a second. Static switches are more expensive but much faster.

Bypass Switch. This is a device used in conjunction with an ATS to provide a means of directly connecting load conductors to a power source and of disconnecting the ATS. Bypass switches may be manual or synchronized.

Uninterruptible Power Supplies

An uninterruptible power supply (UPS) is a system designed to come into operation automatically, with negligible delay and transients, immediately following the failure of the utility supply, and to continue to energize the load acceptably until normal supply is restored. An UPS generally includes generators or energy storage devices or combinations thereof, and ATS, and bypass switches. Redundancy may be incorporated by connecting two or more sources or storage devices in parallel, such that load is transferred simultaneously to all redundant systems. This increases the reliability of the UPS, since the likelihood of simultaneous failure of all the redundant systems is much lower than that of each individual system.

IEEE Standard 446-1987 (1) provides detailed descriptions of components and configurations of emergency and standby power systems. IEEE Standard 493-1990 (3) is an excellent source of power component reliability data. The following section describes and analyzes a typical configuration.

RELIABILITY ANALYSIS OF POWER SYSTEMS

Since the objective of emergency and standby power systems is to enhance the reliability of power supplied to a critical load, it is pertinent to discuss briefly some methods to determine the reliability of such systems and the extent to which such systems improve the reliability of power supplied to the critical load. Several methods of systems reliability modeling and analysis are described in Refs. 3–5. Some of these approaches will be illustrated in this section. These techniques may be suitably adapted to analyze almost any emergency or standby power system.

Sample System Description

Consider the sample system shown in Fig. 1. The critical load normally receives power from utility input power through the UPS. A synchronized bypass and static switch protect the critical load in the event of an inverter failure. If voltage is lost to the critical load, the STS reestablishes voltage in less than one-quarter of a cycle. This is considered continuous power for most loads.

When the generators are in standby mode, their failures remain undetected except during periodic inspections. Therefore, while starting, there is a probability p_s that a generator may fail to start.

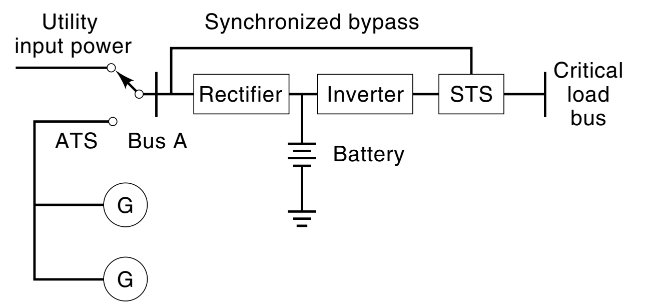

Figure 1. Parallel-supplied nonredundant uninterruptible power supply.

Table 1. System Data

Equipment/Supply		λ (f/y)	r (h/f)
Utility supply, single circuit		0.53700	5.66
Generator (per hour of use)		0.00536	478.00
Inverter		1.25400	107.00
Rectifier		0.03800	39.00
ATS		0.00600	5.00
STS		0.08760	24.00
Battery		0.03130	24.00
Equipment Maintenance		*freq* (/y)	*dur* (h)
Generator		1.00	10.00
UPS		1.00	4.00
Other Data:			
Battery can supply load for			4.0 h
Common mode failure of generators	(λ_{cm})		0.0
Acceleration factor for planned maintenance of generators	(α)		2.0
Probability of failure to start a generator	(p_s)		0.015

Only one generating unit is taken out for planned maintenance. If a generator fails while the other is on planned maintenance, it is possible to accelerate the maintenance on the second generator by a factor of α.

If power fails at bus A, the battery can sustain the load for up to 4 hours.

Table 1 lists the data pertaining to the system. The failure rates (λ) and the failure durations (r) of all the components comprise the required data for analysis.

Two methods of analysis, and the determination thereby of failure rates and durations of supply at bus A and the critical load bus, will now be demonstrated.

Analytical Method

The analytical method described here uses the concepts of Markov chains and Markov cut-sets. A detailed treatment of these techniques is available in Singh and Billinton (4). The method as applied to the sample system is described in Singh, Gubbala, and Gubbala (7).

A *Markov chain* is a sequence of events consisting of the transition of a component or system of components among a set of states such that the state to which the component or system transits in the future depends only on the current state of the component or system and not on the states it has transited through in the past. If a system conforms to (or, more realistically, approximates) this behavior, then the theory of Markov chains may be applied to it. In this kind of analysis, information of interstate transition rates is used to determine the rate of transiting to failure states.

The transition rate from state i to state j is the mean rate of the system passing from state i to state j. The durations of component states are assumed exponentially distributed, which means that the interstate transition rates are constant.

The state probabilities can be obtained by solving

$$BP = C \tag{1}$$

where B matrix obtained from A by replacing the elements of an arbitrarily selected row k by 1; A matrix of transition rates such that the element $a_{ij} = \lambda_{ji}$ and $a_{ii} = -\sum_j a_{ji}$; λ_{ij} constant transition rate from state i to j; $\boldsymbol{P}$ column vector whose ith term p_i is the steady state probability of the system being in state i; $\boldsymbol{C}$ column vector with kth element equal to one and other elements set to zero. Once the steady-state probabilities have been calculated, the reliability indices (4) can be computed using the following relationships.

Frequency of System Failure. The relationship for the frequency of system failure (9) is given by Eq. (2) or Eq. (3)

$$f_f = \sum_{i\in(S-F)} p_i \times \sum_{j\in F} \lambda_{ij} \tag{2}$$

$$= \sum_{i\in F} p_i \times \sum_{j\in(S-F)} \lambda_{ij} \tag{3}$$

where f_f is the frequency of the system failure, S is the system state space and F is the subset of failed states.

Mean Down Time. The expected time of stay in F in one cycle is

$$r_f = P_f / f_f \tag{4}$$

where

$$P_f = \sum_{i\in F} p_i \tag{5}$$

A *cut set* is a set of components that, if removed from the system, results in loss of power to the load point. If this set does not contain any cut set as a subset, then it is called a *minimal* cut set. In this definition, component is used in a wider sense of hardware or a particular system condition. In general, cut sets containing m components are called m-order cut sets. Cut sets are considered up to the second order and the contribution from higher order cut sets is considered negligible. The following relationships are important in cut-set calculations.

1. Frequency and duration of a cut set
   a. First-order cut set (3)

$$f_{cs_i} = \lambda_i \tag{6}$$

$$r_{cs_i} = r_i \tag{7}$$

   where f_{cs_i}, r_{cs_i} = frequency and mean duration of cut set i; λ_i, r_i = failure rate and mean duration of components comprising cut set i

   b. Second-order cut set (3)

$$f_{cs_i} = \lambda_i \lambda_j (r_i + r_j) \tag{8}$$

$$r_{cs_i} = r_i r_j / (r_i + r_j) \tag{9}$$

   where λ_i, λ_j = failure rates of components i and j comprising cut set i; r_i, r_j = mean failure durations of components i and j comprising cut set i

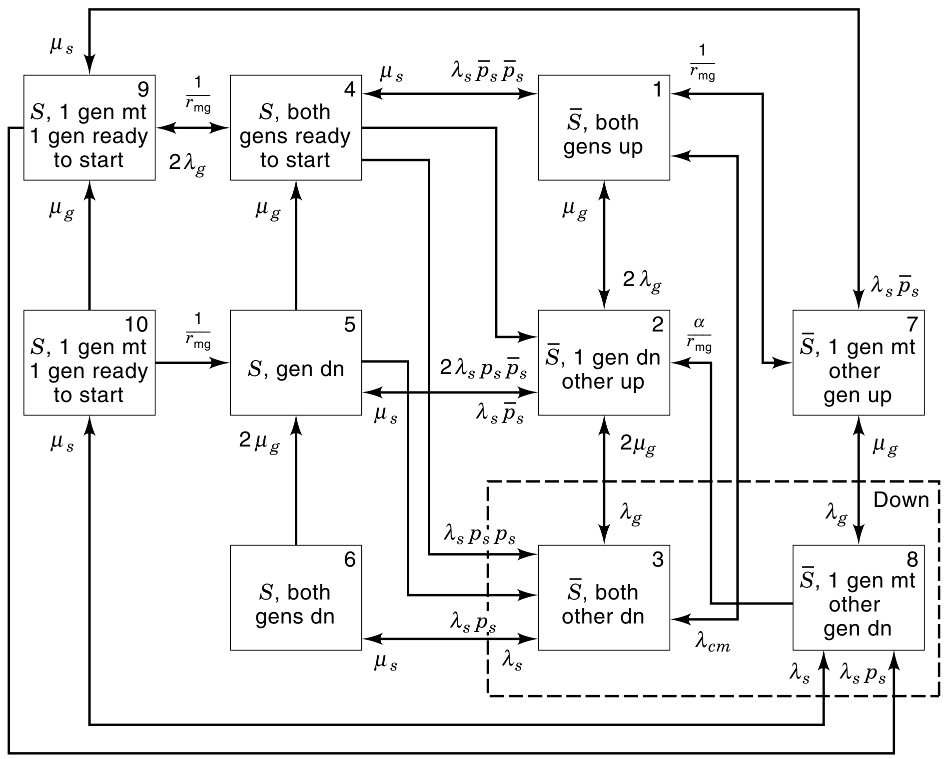

Figure 2. State transition diagram for utility supply and generators. S = Utility power up; $\bar{S}$ = Utility power failed; p_s = Probability of failure to start the generator; $\bar{p}_s$ = $(1 - p_s)$, i.e., probability of starting; λ_g, μ_g = Failure rate of generator while running and repair rate of generator; λ_s, μ_s = Frequency of need to start and shut down the generators. In this case, these parameters equal the frequency of loss and restoration rate of utility supply; λ_{mg}, r_{mg} = Maintenance frequency and duration for a generator; λ_{cm} = Common mode failure of generators; α = Acceleration factor for planned maintenance.

c. Conditional second order cut set (3). Assuming that component i fails given component j has failed,

$$f_{\text{cs}_i} = \lambda_i \lambda_j (r_j) \tag{10}$$

$$r_{\text{cs}_i} = r_i r_j / (r_i + r_j) \tag{11}$$

The terms failure frequency and failure rate are often used interchangeably. Strictly speaking, failure rate is the mean number of failures per unit of the up time, and failure frequency is the mean number of failures per unit of the total time. If the probability of a system being up is close to unity, then these two quantities are very close. In general, failure frequency is less than failure rate.

2. Frequency and duration of interruption (3)

$$f_s = \text{frequency of load interruption} = \sum_{\forall i} f_{\text{cs}_i} \tag{12}$$

$$r_s = \text{mean duration of load interruption} = \sum f_{\text{cs}_i} r_{\text{cs}_i} / f_s \tag{13}$$

The theory concerning Markov chains and minimal cut sets is dealt with in greater detail in Singh and Billinton (4). These concepts are used as follows to analyze the sample system.

First, the combination of the utility supply and the two generators is analyzed for failure modes. Figure 2 shows the possible states this combination can assume, and the transition rates between these states. Based on these transition rates, the probabilities and frequencies of occurrence of the failed states are determined.

Equations (1)–(5) can be used to determine the reliability indices of the utility-generator subsystem:

$$\begin{aligned} f_p &= \text{frequency of loss of power} \\ &= \text{frequency of states 3 and 8} \\ &= P_3(2\mu_g + \mu_s) + P_s\left(\mu_g + \mu_s + \frac{\alpha}{r_{mg}}\right) \end{aligned} \tag{14}$$

$$\begin{aligned} \lambda_p &= \text{frequency rate } = f_p/(1 - P_3 - P_8) \\ &= 0.001576 \text{ failures/year} \end{aligned} \tag{15}$$

$$r_p = \text{mean duration} = (P_3 + P_8)/f_p = 5.443 \text{ h} \tag{16}$$

Equations (6)–(13) are used for the remainder of the analysis. This analysis is summarized in Table 2. Some of the steps are described below.

The first step in analyzing the rest of the system involves computation of the rate and duration of power failure at bus A:

$$\lambda_{\text{A}} = \lambda_p + \lambda_{\text{ATS}} = 0.007576 \text{ f/y} \tag{17}$$

$$r_{\text{A}} = \frac{\lambda_p r_p + \lambda_{\text{ATS}} r_{\text{ATS}}}{\lambda_p + \lambda_{\text{ATS}}} = 5.092 \text{ h} \tag{18}$$

Having determined this, it is necessary to compute the frequency of the event that power loss at bus A will exceed 4 hours, which is the length of time the UPS can sustain the load. Assuming the failure duration to be exponentially distributed, the failure frequency of a cut set having duration $\geq c$ can be found as follows:

$$f_{\text{cs}}(\geq c) = f_{\text{cs}} \text{ (Prob. of event duration} \geq c) = f_{\text{cs}} \exp(-c/r_{\text{cs}}) \tag{19}$$

$$r_{\text{cs}}(\geq c) = c + r_{\text{cs}} \tag{20}$$

Table 2. Summary of Cut-Set Analysis

	Cut Set	λ (f/y)	r (h/f)	λr
1.0	Power loss at bus A > 4 h	0.003454	5.092	0.017588
2.1	Power loss at bus A (0.007576, 5.092)			
	and	0.000125	4.845	0.000606
2.2	Failure of [inverter or battery or STS] (1.3729, 99.812)			
3.1	Maintenance on UPS (1.0, 4)			
	and	0.000003	2.240	0.000007
3.2	Power loss at bus A (0.007576, 5.092)			
4.1	Inverter failure (1.254, 107.0)			
	and	0.001643	19.603	0.032208
4.2	STS failure (0.0876, 24.0)			
	Σ	0.005225		0.050409

Note that although the mean duration of failures greater than c hours is $c + r_{cs}$, the duration of actual loss is r_{cs} as the battery can supply power up to c hours.

The frequency and duration of event 2.2 (see Table 2): this event will occur if the component inverter or battery or STS fails.

$$\lambda_{2.2} = 1.254 + 0.0313 + 0.0876 = 1.3729 \text{ f/y} \quad (21)$$

$$r_{2.2} = \frac{1.25 \times 107 + 0.0313 \times 24 + 0.0876 \times 24}{1.3729} = 99.812 \text{ h} \quad (22)$$

Now events 2.1 and 2.2 can be combined by using Eqs. (8) and (9). Similarly events 3.1 and 3.2 can be combined using Eqs. (10) and (11). It is assumed that a UPS will be taken out on planned maintenance once per year for 4 h. Finally, events 4.1 and 4.2 can be combined using Eqs. (8) and (9).

The system indices, that is, rate and duration of power loss at the Critical Load Bus (CLB) are determined to be

$$\lambda_{\text{CLB}} = \textstyle\sum_{\text{cut-sets}} \lambda = 0.005225 \text{ f/y} \quad (23)$$

$$r_{\text{CLB}} = \frac{\sum \lambda r}{\sum \lambda} = 9.648 \text{ h} \quad (24)$$

In addition to determining the means of the failure rates and durations, it may be useful to be aware of their variances. If all distributions are assumed exponential (see below), then the standard deviations of all the up times and down times would equal the corresponding mean up times and down times. This implies that the standard deviations of the failure rates would also equal the corresponding means computed. It should be understood, however, that even if all the component up times and down times are exponentially distributed, the up time and down time of the system or of any part of the system consisting of a collection of components are not necessarily exponentially distributed, though they may sometimes be approximately represented as such.

Monte Carlo Simulation

This is another method of determining reliability indices. This method is described in detail in Ref. 4, while an application of it to the sample system is given in Ref. 8. A summary of the method is presented here.

The reliability indices of an actual physical system can be estimated by collecting data on the occurrence of failures and the durations of repair. The Monte Carlo method mimics the failure and repair history of the components and the system by using the probability distributions of the component state durations. Statistics are then collected and indices estimated using statistical inference.

Though there are different ways of implementing Monte Carlo simulations, the technique most appropriate for such a system that includes dependent failures is the *next event* method. This is a sequential simulation method which proceeds by generating a sequence of events using random numbers and probability distributions of random variables representing component state durations. A flowchart is given in Fig. 3.

The input data consist of the failure rate (λ) and mean down time (r) of every component. The failure rate is the reciprocal of the mean up time. The mean down time is the reciprocal of the repair rate (μ). The failure and repair rates, λ and μ, of a component will be used to determine how long the component will remain in the 'up' state and the 'down' state.

Simulation could be started from any system state, but it is customary to begin simulation with all the components in the up state.

The time to the next event is generated by using the *inverse of probability distribution* method. This is explained as follows.

The transition times of the components are assumed to be exponentially distributed:

$$f(t) = \rho e^{-\rho t} \quad (25)$$

where ρ is the transition rate. The mean transition time is, therefore,

$$\int_0^\infty f(t)\, dt = \frac{1}{\rho} \quad (26)$$

This means that if, for instance, a component is up, then, regardless of how long it has been in the up state, the expected time to the next failure is $1/\lambda$, that is, the mean up time.

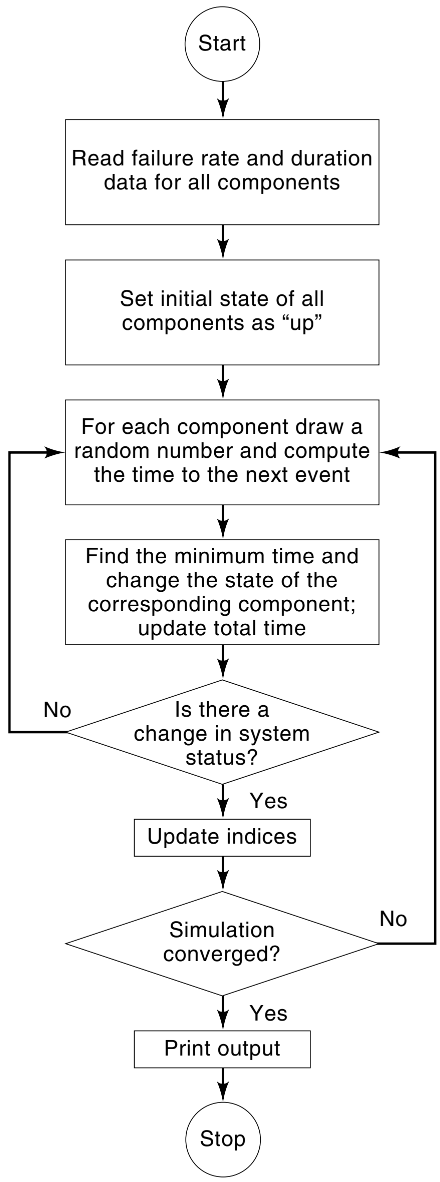

Figure 3. Flowchart for next-event simulation.

The *probability distribution function* of the transition time T would be

$$F(t) = P(T \le t) = \int_0^t \rho e^{-\rho\tau}\, d\tau = 1 - e^{-\rho t} \qquad (27)$$

Now $F(T)$ can be regarded as a random variable, uniformly distributed between 0 and 1. This means that the function

$$S(T) = 1 - F(T) = e^{-\rho t} \qquad (28)$$

is also uniformly distributed between 0 and 1. So if a random number R_n is generated, $0 \le R_n \le 1$, it can be associated with the event that the next transition occurs after time t_r, given by

$$R_n = e^{-\rho t_r}, \quad \text{that is,} \quad t_r = -\frac{\ln(R_n)}{\rho} \qquad (29)$$

This method is used to determine the time to the next transition for every component, using λ or μ for ρ, depending on whether the component is up or down.

At the end of any simulated time interval $[0, t]$, where t = total up time in $[0, t]$ + total down time in $[0, t]$, the estimates of the reliability indices are given as follows.

$$\text{failure rate:} \qquad \lambda_t = \frac{\text{number of failures in } [0, t]}{\text{total up time in } [0, t]} \qquad (30)$$

$$\text{mean down time:} \qquad r_t = \frac{\text{total down time in } [0, t]}{\text{number of failures in } [0, t]} \qquad (31)$$

The values of λ and r at the instant the simulation converges are the reliability indices for the system as obtained from the Monte Carlo method. The simulation is said to have converged when the indices attain stable values. This 'stabilization' of the value of an index i is measured by its standard error, defined as:

$$\eta = \frac{\sigma_i}{\sqrt{n_c}} \qquad (32)$$

where σ_i = standard deviation of the index i; n_c = number of cycles simulated.

Convergence is said to occur when the standard error drops below a prespecified fraction ϵ of the index i, that is, when

$$\eta \le \epsilon i \qquad (33)$$

If, for instance, the mean down time r is chosen as the index to converge upon, then, after every system restoration simulated, the following relation is tested for validity:

$$\frac{\sigma_r}{\sqrt{n_c}} \le \epsilon r \qquad (34)$$

If this criterion is satisfied, the simulation is said to have converged.

Simulation is advantageous in that it not only allows the computation of indices at various points in the system, but also permits the accumulation of data pertaining to the distribution of these indices, thereby affording a better understanding of the system's behavior.

For an emergency power system, for instance, statistics may be collected for failure frequency and duration at various points in the system, the annual incidence rates for failures, as well as for the variances of these indices. Table 3 shows the estimates obtained for the following statistics using

Table 3. Reliability Indices of Sample System

	Simulated		Calculated	
Index	*Mean*	*SD*	*Mean*	*SD*
λ_p (f/y)	0.001352	0.001497	0.001576	0.001576
r_p (h/f)	5.028	5.503	5.443	5.443
λ_A (f/y)	0.007193	0.006851	0.007576	0.007576
r_A (h/f)	5.216	5.201	5.092	5.092
λ_{CLB} (f/y)	0.004868	0.004888	0.005225	0.005225
r_{CLB} (h/f)	9.7135	13.3312	9.648	9.648

Monte Carlo simulation, and compares them with the corresponding values as determined by the analytical method described earlier.

Improvement in Reliability of Supply

The above discussion illustrates not only the methods of analysis, but also that the reliability of the supply to the critical load bus is significantly improved by the presence of an uninterruptible power supply. Note that the utility supply has a failure rate of 0.537 failures per year, while the supply to the critical load bus has a failure rate of only 0.005 failures per year. This demonstrates the role and objective of an emergency power supply.

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EMG. See ELECTROMYOGRAPHY.
EMISSIONS, FROM POWER PLANTS. See AIR POLLUTION CONTROL.