UPS Reliability and System Configurations

MGE UPS SYSTEMS

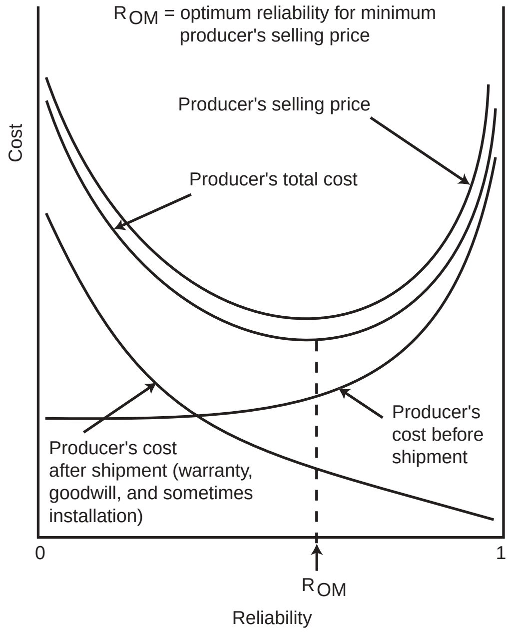
ABSTRACT *- Maximization of computer uptime is essential to the profitable operation of any corporation. Of all the elements that support a large data processing application, the UPS is probably the least understood in terms of reliability and availability. This paper demystifies the process of configuring a reliable UPS and offers some simple guidelines and principles that are universal to any emergency back-up system. In particular, this paper also reviews the current trend towards improved system flexibility and why this may not improve system reliability. Included is a comparative reliability analysis of the most popular UPS configurations to illustrate key reliability issues and examples on how the simple reliability guidelines and principles are applied.*

INTRODUCTION

The primary reason for the purchase of a UPS system is to dramatically improve the reliability and quality of electrical power to critical loads. Therefore it is important to study the reliability of the UPS system itself, and be confident that the chosen system configuration meets the needs of the particular loads which the UPS is to protect.

Some users are primarily concerned with the initial cost of the system alone, and do not pay attention to the installation, maintenance and service costs. More importantly, in many cases, the costs incurred due to down time of the critical load are overlooked. A system developed with reliability in mind, will not only have the optimum reliability for the customer, but also low costs to the manufacturer of the UPS system (See figure 1). It is important to recognize that the most “exotic” system may not necessarily be the most reliable and cost-effective system. A price in terms of reliability may have to be paid when feature and functions are added to make the system “unique”. The study of reliability not only concerns the reliability of the hardware, but also reliability associated with operational scenarios and operator characteristics.

Figure 1. Product Cost vs. Reliability



Another consideration in selecting the right system is to clearly understand the difference between reliability and flexibility. Flexibility in all cases does not buy reliability and vice versa. A close examination of the type of loads, power demands of those loads, level of protection desired and degree of flexibility needed for individual loads or clusters of loads should be made before deciding on the type of UPS system.

THE BASICS

Mean Time Between Failure (MTBF):
This is defined for products that can be repaired back to their original state of operation after a failure. It is defined as the average time span between failures. The inverse of MTBF is the failure rate is and is denoted by λ.

Meant Time to Repair (MTTR):
It is defined as the average time in which the failure can be repaired. The inverse of MTTR is denoted by μ.

Availability:
Availability is defined as:

$$A = \frac{MTBF}{MTBF + MTTR}$$

The definition of availability does not take into account the down times due to preventative maintenance and other administrative reasons.

Bathtub Hazard Rate Curve:
This curve very closely represents the failure rate of most electronic and electrical components and systems. Additionally, it is made up of three distinct phases a product encounters in its life. Please see Figure 2. They can be represented by three distinct probability distributions. For general applications, however, the Poison's Distribution is used to represent the entire curve for simplicity. The following are the relations which describe a Poison's distribution.

$$(t) = \lambda e^{-\lambda t}$$

$$F(t) = 1-e^{-\lambda t}$$

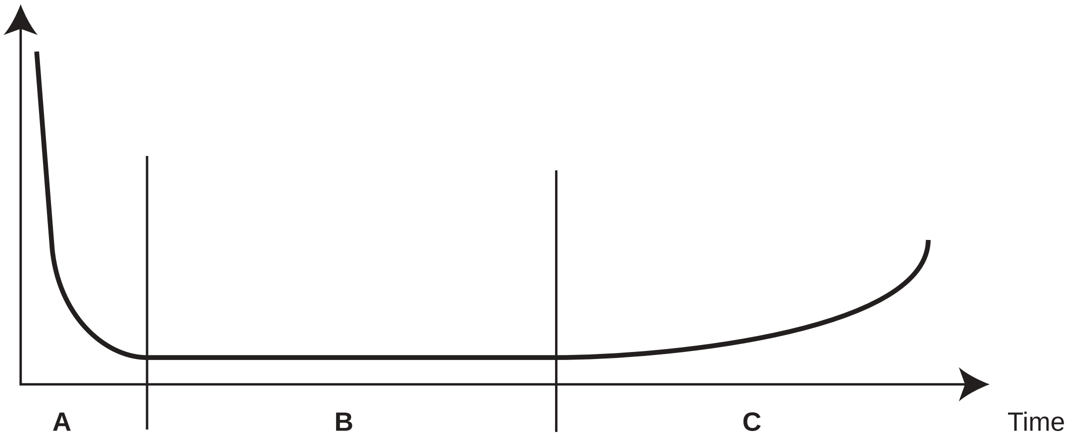
$$R(t) = e^{-\lambda t}$$

$$h(t) = \lambda$$

$$MTBF = 1/\lambda$$

Infant mortality occurs due to premature failure of components, pooer assembly methods and poor quality control. Most of these failures can be eliminated y proper testing and burn-in of the UPS system at the plant. The middle section of the curve represents the useful life of the system and it can be considerably increased by correct and preventative maintenance. The final phase is the wear-out phase where failure rates start to increase because of aging of components. Failures typically increase exponentially with time.

Figure 2. Bathtub Hazard Rate Curve



A = Infancy Failures **B** = Random Failures
C = Wear Failures

STUDY OF RELIABILITY

A proven method in the study of reliability is the use of reliability diagrams. The starting point of the process is to come up with the physical and electrical diagrams. These diagrams can be converted into reliability block diagrams by the use of simple logic. Complicated circuits and scenarios can be evaluated, and reliability diagrams systematically constructed, by applying the concepts and techniques available in set theory, probability theory and network analysis. Once these diagrams are constructed, and if reliability data for individual blocks that make up these diagrams is available, the total system reliability can be determined.

The following methods are used to find out the reliability of individual components or blocks of the reliability diagram:

1) Parts Count Method:

   This method involves categorizing the components into various groups or subassemblies, adding to them the failure rates attributable to putting the assemblies together and combining the failure rates to come up with the overall failure rate of the system.

2) Laboratory Method:

   This method takes into account laboratory reliability predictions and combines them with the failure rates of components on a weighted average basis.

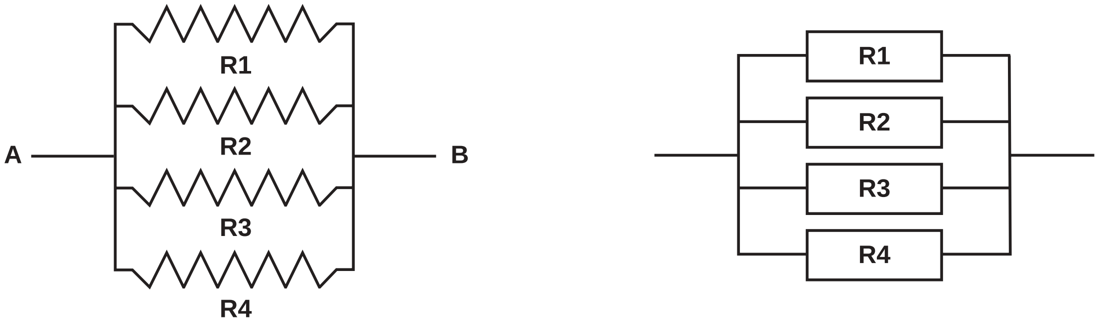
3) Field Method:

   This method relies on observations made in the field on actual failure rates. This method can be successfully used only if a well-designed field tracking system is in place which can distinguish between various failure modes and analyze those modes in detail. A well designed tracking system for inventory and traceability of parts is required.

In order to illustrate the basic logic used to construct reliability diagrams from electrical schematics, the simple example of four resistors in parallel shown in Figure 3 will be used. The goal is to accomplish the flow of current from Point A to Point B without overloading the resistors.

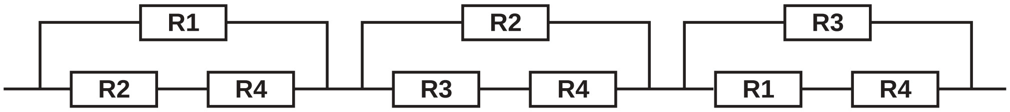
> **Case 1:** In this case the resistors are assumed to be such that any one of them can carry the full load current without overheating and ultimately failing. For this situation the reliability diagram will be exactly the same as the electrical diagram. It is important to note that because of the redundancy of resistors, there are four paths available to go from Point A to Point B in the redundancy diagram.

Figure 3. Reliability diagrams for resistors in parallel



(A) Four resistors in parallel

(B) Case 1- Each resistor capable of full load current



(C) Three out of four must be in service

(D) All must be in service

> **Case 2:** In this case it is assumed that the failure of more than one of the resistors will cause an overload on the remaining resistors. In this situation the diagram is constructed by evaluating the different possibilities of resistor failures and how they affect the flow, and then combining the blocks together to represent the overall scenario.
>
> **Case 3:** This time the failure of any one resistor causes the overload. The resultant reliability diagram will comprise of four elements in series signifying the fact that failure of any one would prevent the flow from Point A to Point B.

The above analysis clearly shows that the old adage “a chain is as strong as its weakest link” has complete congruence with the study of reliability by the use of reliability diagrams. It can also be deduced that adding more components in the path of the flow of current (blocks in series in the reliability diagram) has the effect of decreasing the reliability of the system unless the reliability of the added components approaches infinity.

SYSTEM DESIGN EVALUATION

The optimization of reliability for any complex system be it a UPS or a factory, requires careful consideration of a variety of factors. Not the least of these is the fundamental concept that the system and all its elements must be kept as simple as possible to meet specified performance criteria. It deserves repeating that the more complex a system, the higher the number of critical components, the lower the overall reliability; given all other things being equal. Chart 1 illustrates this principle. Large electrical systems with many redundant parallel switching paths must keep this in mind. Each automatic switch that provides a redundant power path to the load is by itself a critical component and forms series block in the reliability diagram, and thus figures into system reliability. Too many of these components may have the opposite desired affect.

Number of Critical Components	**Individual Component Reliability**			
	99.999%	**99.99%**	**99.9%**	**99.0%**
	System Reliability			
10	99.99%	99.99%	99.00%	90.44%
100	99.90%	99.01%	90.48%	36.60%
250	99.75%	97.53%	77.87%	8.11%
500	99.50%	95.12%	60.64%	0.66%
1000	99.01%	90.48%	36.77%	<0.1%
10,000	99.48%	36.79%	<0.1%	<0.1%
100,000	36.79%	<0.1%	<0.1%	<0.1%

Chart 1. The relationship between system and critical component reliability[1]

In summary, the following lists the most important factors to consider for optimal UPS system reliability:

1. System complexity. Keeping the UPS system design as simple as possible not only pays off in terms of product cost, but in reliability as well. The more complex the system, the lower the overall reliability.
2. Standard versus custom design. UPS manufactures have spent years optimizing their standard designs to maximize reliability. As is true with any complex system, customizations to the standard design add to the complexity of the product and negatively affect reliability. Benefits and requirements of a customized product must be considered carefully.
3. Ease of operation. A well designed UPS system will be easy to operate and work automatically in normal use. Complicated switching arrangements with many manual controls are not desirable for critical applications where the risk of operator error is unacceptable.

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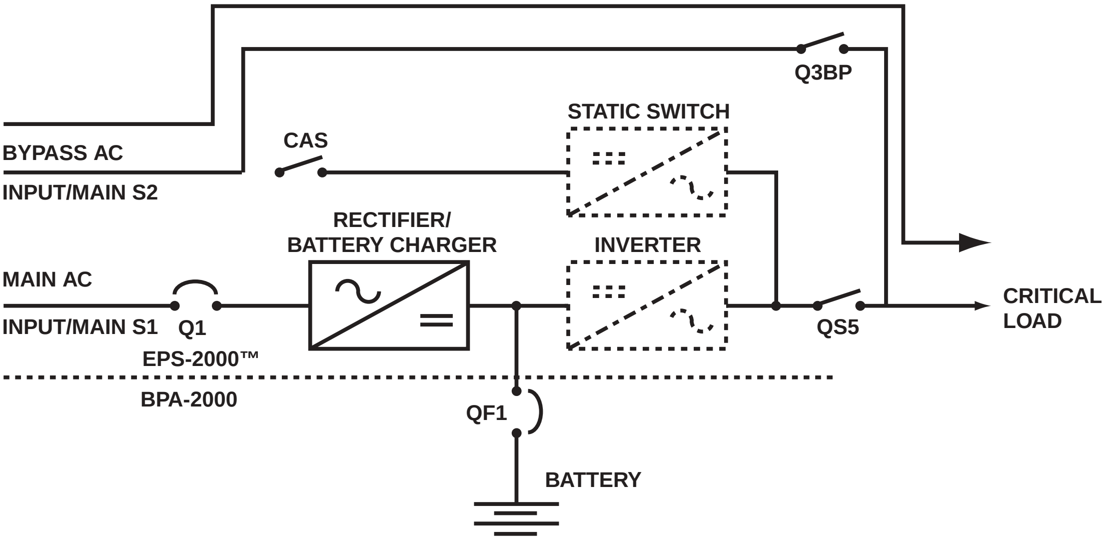
[1] Kececioglu, Demitri Reliability Engineering Handbook, Chapter 1, page 5.

4. Environmental conditions. Care and planning of the installation of a UPS system to comply with the manufacturer's recommendations for temperature, humidity and acceptable clearances are extremely important. Failure to meet these requirements is the leading cause of premature UPS failures.
5. System maintainability. A UPS system must be designed to ease maintenance, to maximize availability and therefore achieve the highest reliability. Items which should be standard in the design of the UPS system include fully isolated, maintenance bypass switches, field replaceable modules to facilitate quick repairs, and easy access to all equipment.
6. System performance specification and coordination. Planning of the entire power system of which the UPS is a part must include detailed coordination of interrupting capacities, stand-by power sources, harmonic currents, etc. Unnecessary stress on the system can result in many "unexplained" errors when this detailed coordination is not carefully specified.
7. Manual versus automatic control. Manual control is always less desirable than automatic control as mentioned in point 3 above. However, exercise caution when the automatic controls are used in excess. Careful planning to reduce the number of automatic controls by grouping controls at the system level whenever possible, will reduce the number of critical components and improve system reliability.

FLEXIBILITY AND RELIABILITY

Flexibility, defined as the ability to re-configure the UPS system to perform maintenance and to bypass equipment, does not always improve reliability. The key to reliability improvement in a UPS is not to make it more flexible, but to improve system availability. If a circuit does not improve system availability, there can be no improvement to reliability. In the case of a UPS, availability can only be improved by an uninterrupted automatic tansfer to another source. Any UPS system that is flexible with multiple configurations through manual tie breakers and switches is not inherently more reliable than one which has no flexibility.

Figure 4. Single module UPS with static switch and maintenance bypass



Consider the simple case of a single UPS with a static bypass switch and a maintenance bypass (refer to figure 4). The static switch provides the flexibility to re-configure the flow of power through the bypass circuit to feed the critical load in the event of an internal failure or overload condition. Since this operation is automatic and transparent to the critical bus, it has the effect of improving system availability and therefore reliability. The maintenance bypass performs much the same function. However, its circuit is manual and thus does not improve availability and reliability of the system. Of course, the maintenance bypass circuit is critical to easing maintenance, but as a power circuit does nothing to improve reliability.

Is there such a thing as too much system availability improvement? Yes, if the complexity of the system is not considered. An example of such a situation is the alarming trend in UPS system designs for redundant power paths to be taken to the point of distribution, with automatic switching at a Power Distribution Unit (PDU) or breaker panel. The desired effect of such a system is improved overall reliability (redundant power paths to each point of distribution), and improved flexibility for maintenance (automatic switches). In actuality, this type of design degrades reliability due to the number of automatic switches (refer to point 7 above). By reducing the complexity of such a scheme – perhaps the substitution of automatic for manual switches – actual reliability is improved and flexibility is maintained.

UPS RELIABILITY – SOME SPECIFIC EXAMPLES

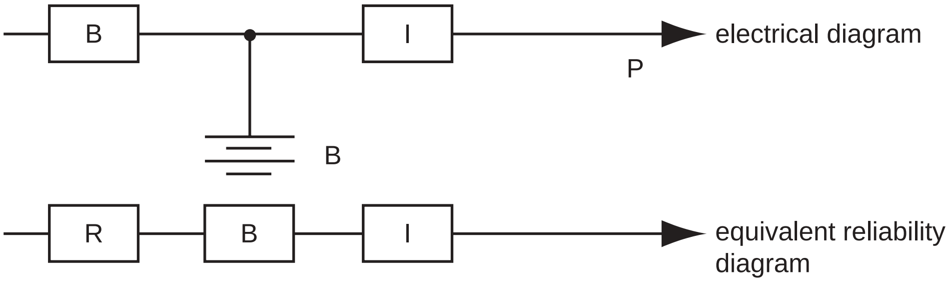
To illustrate the principles described above, the following are some specific examples of UPS reliability and availability. Actual statistical failure data is used for the calculations.

ACTUAL STATISTICAL FAILURE DATA

Function	**MTBF**	**Values (1/λ)**
Rectifier-charger	MTBFR	100,000h
Battery	MTBFB	120,000h
Inverter	$MTBF_I$	70,000h
Fast Acting Switch (FAS)	$MTBF_{FAS}$	500,000h
Mains 2 Static Switch	$MTBF_{S/S}$	500,000
High Quality Utility	$MTBF_{util}$	100h
Medium Quality Utility	$MTBF_{util}$	50h
Mean Time to Repair	MTTR	6h

CASE 1 – UPS WITHOUT STATIC BYPASS

This example illustrates reliability calculations for the power train of most static on-line UPSs. The reliability diagram illustrates that the main elements of the UPS form are connected in series. Using the relations of Poison’s distribution, the overall reliability is calculated as shown. The weakest link in the diagram will have the most impact on reliability.



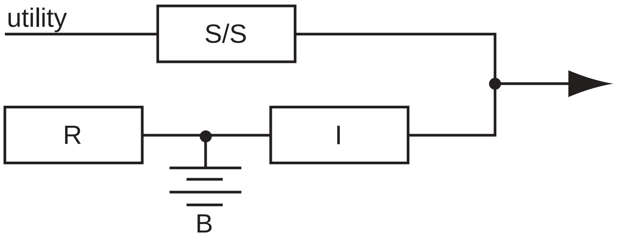
$$\frac{1}{MTBF_{TOTAL}} = {}_{TOTAL} = \frac{1}{MTBF_R} + \frac{1}{MTBF_B} + \frac{1}{MTBF_t}$$

$$TOTAL = \frac{1}{100000} + \frac{1}{120000} + \frac{1}{70000} = \frac{1}{31000}$$

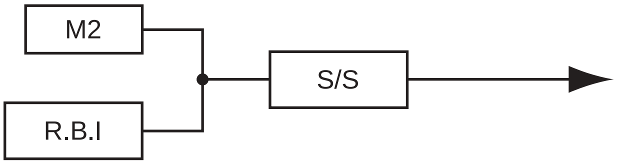
$$\boxed{MTBF_{total} = 31,000 \text{ hours}}$$

CASE 2 – UPS WITH STATIC BYPASS

The addition of a static bypass in a UPS introduced the reliability of both the bypass source and the static switch into the overall reliability calculations. The equivalent reliability diagram illustrates that there are two parallel sources of power available to the critical load. The availability of the bypass as a parallel source is illustrated in the equivalent reliability diagram as a parallel block. The static switch is shown as a series element because it is involved in both the forward and reverse transfer of the UPS. The “RBI” block represents the combined reliability of the rectifier, battery, and inverter as shown in the case 1 above. Depending on the quality of the bypass source the reliability is impacted as shown in the calculations that follow.



electrical
diagram



equivalent
reliability
diagram

The $MTBF_{TOTAL}$ may be calculated using the formula:

$$\frac{1}{MTBF_{TOTAL}} = \lambda_{total} = \frac{1}{MTBF_{US} + MTBF_{UTIL} + \dfrac{MTBF_{US} \times MTBF_{UTIL}}{MTTR}} + \frac{1}{MTBF_{S/S}}$$

- with a high quality Utility: $\text{MTBF}_{\text{TOTAL}} = 100$ h

$$\lambda_{\text{total}} = \frac{1}{31000+100+\frac{31000\text{x}100}{6}} + \frac{1}{500000} + \frac{1}{500000} \approx \frac{1}{261000}$$

$$\boxed{\text{MTBF}_{\text{TOTAL}} = 261{,}000 \text{ hours}}$$

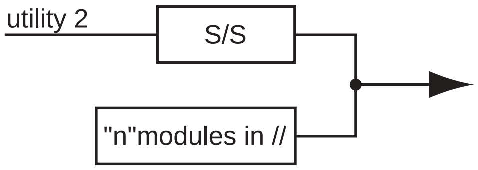
- with a medium quality Utility: $\text{MTBF}_{\text{TOTAL}} = 50$ h

$$\lambda_{\text{total}} = \frac{1}{31000+50+\frac{31000\text{x}50}{6}} + \frac{1}{500000} \approx \frac{1}{183000}$$

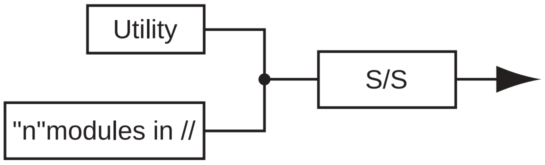
$$\boxed{\text{MTBF}_{\text{TOTAL}} = 183{,}000 \text{ hours}}$$

CASE 3 – UPS WITH SEVERAL UNITS IN PARALLEL

This describes the general case of a UPS system where several modules in parallel are feeding a common output bus, and with a bypass source and static switch rated to supply the entire system. The equivalent reliability diagram is quite similar to Case 2, except that the UPS modules represent a parallel block in the diagram. The reliability of the parallel block is calculated separately depending on the number of UPS modules in parallel and the number of redundant UPS modules. In this example the equivalent reliability diagram and the mathematics are only for the case where each module can supply full load and each UPS is a parallel source.



electrical
diagram



equivalent
reliability
diagram

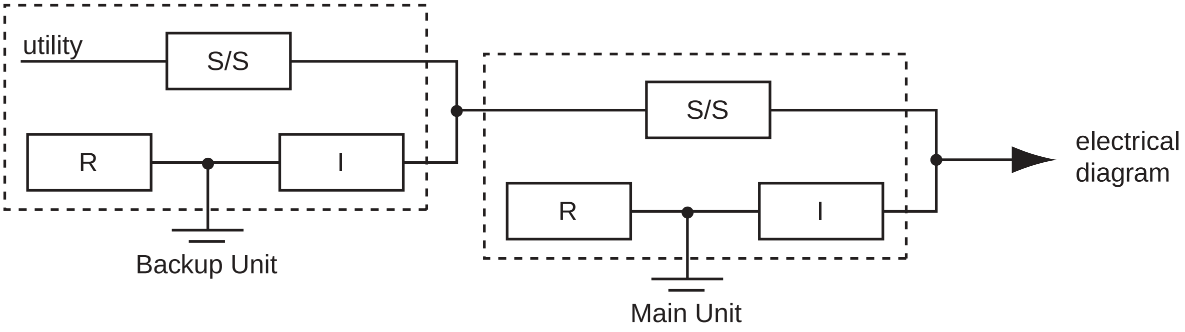
The MTBF total may be calculated using the following formula:

$$\frac{1}{MTBF_{Total}} = \lambda_{total} = \frac{1}{MTBF_{n} + MTBF_{util} + \frac{MTBF_{n} \times MTBF_{util}}{MTTR}} + \frac{1}{MTBF_{s/s}}$$

In which $MTBF_n$ represents the MTBF of "n" lines in parallel

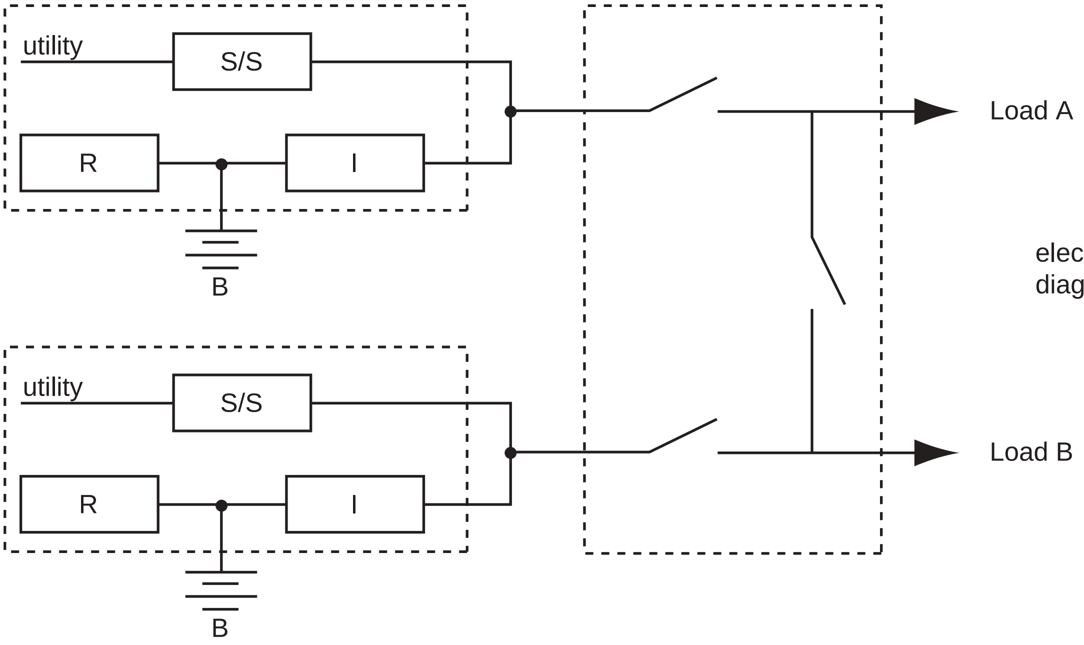
CASE 4 – UPS IN ISOLATED REDUNDANT CONFIGURATION

This example details the use of one UPS as the bypass power source for another UPS, commonly referred to as an Isolated Redundant configuration. The equivalent reliability diagram shows the backup unit forms a parallel block for the bypass source. The mathematics applied in this case is the same as used in Case 2, with the back up unit reliability substituted for the reliability of the utility. The results show that with such a high availability for both parallel sources, the overall reliability is only limited by that of the bypass static switch.



CASE 5 – UPS CONFIGURED WITH MATRIX SWITCH

This is a case where two independent parallel systems are tied together using a matrix switch. The introduction of the matrix switch does not improve the overall reliability of the system since it is usually used for maintenance purposes only. The operation of the matrix switch is completely manual, or at best semi-automatic still requiring manual intervention. This has no benefit in normal operation and can be a concern if care is not taken to minimize operator-related errors. This is a good example of how the introduction of additional elements into a system to improve flexibility does not improve reliability. In fact, when done improperly this can add series elements (operator error) and degrade reliability. This does not take into account the complexities introduced by additional logic and controls which also form series elements with the reliability block diagram. In the best case, the equivalent reliability diagram is a single module to each load. The calculation of reliability this is that of a single module as presented in Case 2.



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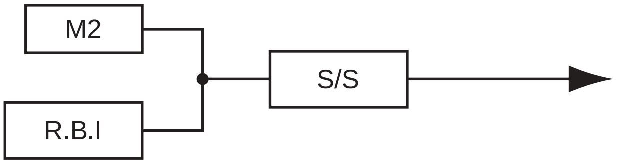

equivalent
reliability
diagram
to each load

$$\frac{1}{\mathrm{MTBF}_{\mathrm{Total}}} = \lambda_{\mathrm{total}} = \frac{1}{\mathrm{MTBF}_{\mathrm{US}} + \mathrm{MTBF}_{\mathrm{util}} + \dfrac{\mathrm{MTBF}_{\mathrm{US}} \times \mathrm{MTBF}_{\mathrm{util}}}{\mathrm{MTTR}}} + \frac{1}{\mathrm{MTBF}_{\mathrm{s/s}}}$$

MTBF of the Configuration with a medium quality utility (50 h)

$$\lambda_{\mathrm{total}} = \frac{1}{31000+183000 + \dfrac{31000 \mathrm{x} 183000}{6}} + \frac{1}{500000} \approx \frac{1}{500000}$$

$$\boxed{\mathrm{MTBF}_{\mathrm{TOTAL}} = 500{,}000 \text{ hours}}$$

SUMMARY OF RESULTS

	MTBF in Hours			
System Configuration	**Without Utility Backup**	**Medium Quality Utility**	**High Quality Utility**	**Isolated Redundant UPS Backup**
Unitary system	31,000	183,000	261,000	500,000
2 lines in//without redundancy	15,500	112,000	177,000	
2 lines in // with 1/2 redundancy	250,000	411,000	450,000	
3 lines in // with 1/3 redundancy	166,000	380,000	430,000	
2 rec/charge 1 battery 2 inv. 1/2	185,000	387,000	433,000	

CONCLUSION

The reliability of UPS systems can be estimated and compared by using the rules and methods presented in this paper. Careful planning and application of these principles can raise the confidence level that the selected system is one that will meet the reliability goals of the end user. The use of reliability diagrams provides an excellent tool for identifying weak points in the system that can be eliminated or improved upon. Reliability and flexibility should be viewed independent of each other and proper weight should be given to both, depending on specific user requirements.

REFERENCES

1. Dhillon, Balbir S., System Reliability, Maintainability & Management, 1983, Petrocelli Books, Inc.
2. Doty, Leonard A., Reliability for the Technologies. 1989, Industrial Press, Inc.
3. Endrenyi, J., Reliability Modeling in Electric Power Systems. 1978, John Wiley & Sons.
4. Fiorina, Jean-Noel; Chevalier, Marcel *A Simple Approach to the Reliability of UPS Architectures*, Power Quality Paris, November 1990 Proceedings.
5. Ireson, W. Grant & Coombs, Jr., Clyde F., Editors in Chief, Handbook of Reliability Engineering & Management, 1988, McGraw Hill.
6. Kececioglu, Dimitri. Reliability Engineering Handbook, 991, Prentice Hall.
7. Department of Defense, Military Handbook, 217F, December 2, 1991.