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Power Systems

The Reliability of the Individual UPS

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1 Introduction

Reliability is a device characteristic and describes the probability of a piece of equipment or system fulfilling the required functions under given conditions and during a given time period. For an uninterruptible power supply system (UPS), reliability means an uninterrupted supply to the loads at a predetermined voltage quality.

Today, complex arrangements of several UPS systems achieve a very high degree of reliability. They ensure that a fault in one or sometimes several UPS systems does not also lead to a failure of the supply to the secure busbar. This is guaranteed by a redundant system configuration. Redundancy can be realized in different ways by parallel connection to a common bus or by a combination of independent units with some multiple redundancy. It raises the question: does the reliability of the individual UPS systems still have an important influence on system reliability or is this only determined by the system configuration? Were the latter to be the case then, nevertheless, highly-reliable systems could be built with an appropriate number of "unreliable" and "cheap" UPS modules. It will be shown that this is not true, rather that the individual systems have a decisive influence on system reliability in all configurations.

2 Reliability of individual UPS systems

Examination of the reliability of individual UPS systems assumes examination of the individual possibilities of failure and the probability of their occurrence. The following sections provide an overview of the various terms and their significance to the reliability calculation.

2.1 The terms MTBF and MTTR

The terms MTBF and MTTR refer to repairable systems in which a fault can be repaired and following repair, the unit is able to carry out its function again under the given conditions. The mean time between two failure periods, i.e. the failure-free operating time, is termed "mean time between failures" (MTBF). The mean time during which the unit is inoperative is the "mean down time" (MDT). This time includes the mean repair time, denoted by the term "mean time to repair" (MTTR). In the literature and in calculations the term MTTR is frequently used instead of MDT. The time from fault occurrence to fault occurrence is then given by the sum of MTBF plus MTTR. The MTBF is usually several orders of magnitude longer than the MTTR.

If a part or a functional module in a system is redundant, it can fail without the essential function of the entire system failing. But it must be repaired or replaced before the redundant partner also fails. Due to the fact that the MTBF is usually much greater than the MTTR, the probability of a double failure is very low. Consequently, a system with built-in redundancy has considerably higher reliability compared to one without redundancy.

Redundancies can be built into units and also realized in systems incorporating several units together.

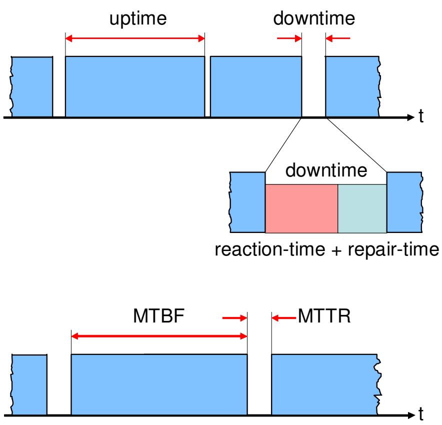


Figure 1 Reliability terms

2.2 The difference between MTBF and availability

Availability A is used in addition to MTBF as one of the characteristic values for the degree of reliability. It is defined by the ratio of MTBF to total time MTBF + MTTR, so

$$A = \frac{MTBF}{MTBF + MTTR} \qquad (1)$$

Whereas MTBF is directly related to the failure rate (failure rate λ = 1/MTBF), and therefore says something about the absolute frequency of the fault, availability is a measure of the usability period of the unit in relation to the total time and says nothing about the absolute failure rate.

A clear distinction must therefore be made between these variables.

Availability is usually represented in the form 0.9999…. Frequently, only the number of nines after the decimal point is stated, where many nines are usually associated with a highly reliable system. But the availability still says nothing about the mean frequency of the occurrence of faults and different pairs of MTBF and MTTR can result in identical availability values. Figure 2 shows examples of different failure rates of 10 years, 1 month and 1 day, which result in correspondingly graded failure times of 1 hour, ½ minute and 1 second for the same availability A=0.99988.

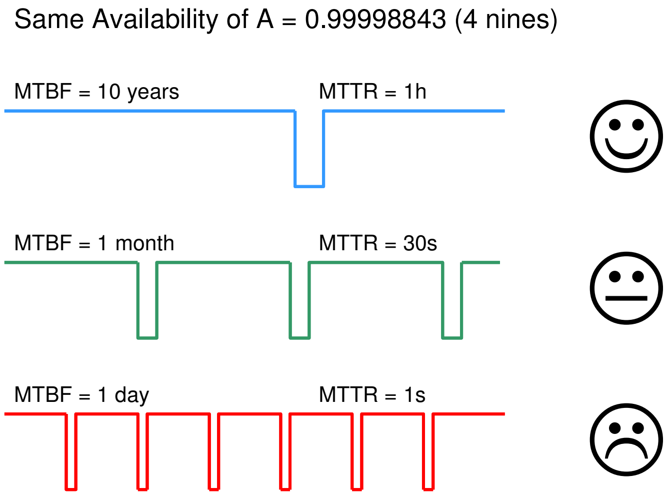


Figure 2 Different MTBF values for the same availability

It is obvious that for an IT application the last case would certainly lead to serious problems, whereas the first case is clearly more acceptable.

2.3 Importance of large numbers

The time period that is necessary for the repair of a unit (MTTR) normally varies in the region of hours or days. This time is counted from the moment the failure occurs up to the point at which the unit is returned to the functioning status and includes reaction and travel times of the service personnel, as well as the actual repair and also the test times.

The usable time (MTBF) varies between several tens and hundreds of thousands of hours, that is to say several years, and values of some hundred years can be assumed for redundant systems. These values are purely statistical figures and the MTBF must not therefore be mistaken for the service life of a system. An individual system may possibly not fail at all during its service life, others perhaps several times. The statement of an MTBF value of one million hours (= 114 years) should be taken to mean, for example, that, within a group of 1000 equivalent units, one unit can be expected to fail every 1000 hours (= 6 weeks). From this viewpoint an increase in the MTBF from one million to 1.2 million hours, for example, definitely represents a meaningful improvement. In the example given above, the (statistical) interval between two failures would consequently be extended to 7 weeks.

2.4 Components and design

The reliability of a UPS system is based on the reliability of its components, where their tasks and the importance of their function within the module are also of significance. One of the main problems for the UPS manufacturer is therefore to choose and incorporate suitable components which can reliably and permanently fulfil their function in the UPS system, given the constraints imposed.

Here the main task that falls to the developer is to select the correct components from the point of view of functional suitability and the expected environmental conditions. In addition to suitable dimensioning for nominal operation, it is sensible to allow a margin for the key data of the components in order to improve reliability, so that for overload or overvoltage conditions, for example, the reliability data do not have to be downgraded or components exposed to premature ageing.

The environmental conditions for which the UPS system has been designed are described in the data sheet in the form of tolerance ranges. However, the conditions for individual components within the unit may possibly deviate from these. This applies, for example, to local operating temperatures to which individual components can be exposed according to their cooling conditions and the influence of neighbouring components. Apart from careful design which is based, not least on the manufacturer's experience, all possible applications of a UPS system must therefore be considered and thoroughly tested in order to guarantee its reliable operation later on.

2.5 Maintenance and service life of components

Redundant UPS systems allow faults in individual modules without the entire system losing its functionality. The probability of a double fault which could result in the interruption of the secure power supply to the load increases with the MTTR of the module, i.e. with the necessary mean time to repair. The same also applies to service work on components which require regular maintenance, such as fans or capacitors, for example, since also during this time the unit is not available to the system. The construction of the UPS system should therefore be of a type that allows repair and maintenance operations to be carried out with only short down-times. The maintenance intervals also determine the frequency of shutdowns, which in turn influence the mean down-time. An extension of the maintenance intervals can be achieved for example by increasing the service life of the relevant components to a maximum. This is achieved, for example, by lower utilization and low operating temperatures. Ideally, components are used which require no regular maintenance, which is the case for example if chokes are used instead of capacitors in filter circuits, provided that this is allowed by the system concept.

Incidentally, experience shows that faults often occur in a UPS system during or after work on the individual units. Also in this respect the selection of low-maintenance components leads to an increase in reliability of the individual UPS units and consequently that of the system as well.

Frequent mention is made of a critical fault when the required function is no longer fulfilled, i.e. when in the case of a UPS system the supply to the load is no longer guaranteed. For many technical units, especially standard equipment, the failure rate (λ = 1/MTBF), that is to say the number of faults per time, is represented by a so-called bathtub curve. Figure 3 shows the basic characteristic.

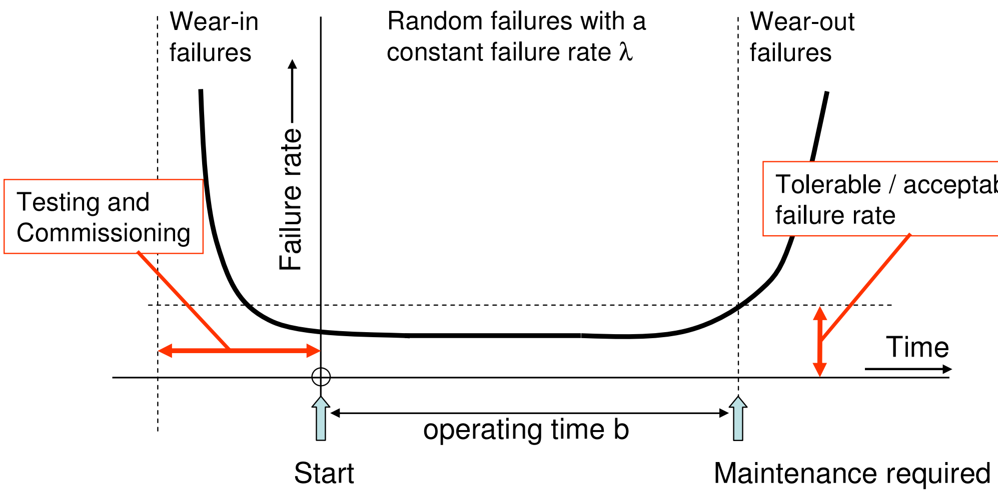


Figure 3 Typical characteristic curve of the failure rate of technical systems (Bathtub curve)

Following the commissioning of a piece of equipment, its failure rate is initially relatively high. This period is denoted "burn-in" and should elapse before the component is used for the actual function. This usually happens during the test and commissioning phase. A longer time interval with virtually constant and low failure rates over the service life of the product follows the "burn-in" phase. At the end of the service life the fault rate rises again due to wear effects.

The time at which maintenance occurs or the end of the useful life of the components is determined by the tolerable or acceptable failure rate. All reliability calculations are based on the constant failure rate in the central region of the curve.

For the reliability calculation following a repair or component replacement, it is assumed that the failure rate is again located at the bottom of the bathtub curve. At the same time, replacement parts must have passed through the "burn-in" phase. In addition, trouble-free operation of the replacement part inside the equipment should be ensured by appropriate tests, before the UPS system is again finally put into service. So-called "plug-in" solutions, in which individual components are required to be immediately fully functional without a final test, are questionable for high-reliability systems.

2.6 Redundancy

Regarding its reliability, apart from a low component failure rate, internal functionality is the second most important characteristic of a UPS system and is particularly reflected in its reaction to the failure of individual components. Failure-tolerant performance exists if, in the event of a component failure, it is possible to switch over to a reserve component or a reserve group, without the supply to the load being interrupted at the same time. In the end this leads to the term redundancy which describes the state of readiness of parallel branches. In UPS systems, specific redundant or partially-redundant branches are usually provided, such as the bypass path for example, which in the event of a failure of one of the main components makes it possible to continue operation – even if with limited functionality.

The mode of operation of a redundant function will now be explained by means of the example of the diode function (Figure 4). With an individual diode, an internal short-circuit or open-circuit inevitably leads to malfunction. A series circuit of two diodes controls the short-circuiting of one diode without outwardly impairing the overall functionality, whereas an open circuit results in failure. A parallel circuit of two diodes controls the open-circuit of one diode, whereas now the short-circuit leads to failure. Full redundancy for both cases of failure is only possible by means of a circuit having four diodes, by connecting two groups of two series-connected diodes in parallel.

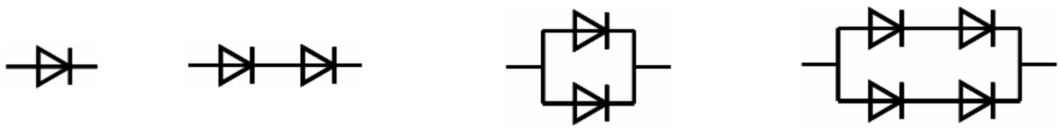


Figure 4 Different types of redundancy

The prerequisite for practical, redundant operation is a system that is capable of being repaired. Moreover, it is imperative that the faulty component is reliably detected by the internal monitoring functions to facilitate its replacement before a further fault occurs.

This principle can be applied to the redundant operation of UPS systems. In the event of a failure in the inverter of a UPS, the function of an open circuit is undertaken by a parallel-connected branch, in this case the redundant UPS, whereas a short-circuit must initially be transferred to the open-circuit state with the aid of fuses or fast electronic switches.

An individual UPS system does not usually contain any redundant branches of numerous identical components. Where available, the bypass branch offers redundancy with limited functionality. This is termed pseudo redundancy. In static systems this branch is provided internally or externally anyway for continued supply to the load in the case of overloads and short-circuits, so that additional components are not even necessary for redundancy in this case. Therefore full redundancy is not obtained since, in the bypass mode, the unregulated mains is connected to the load.

In many UPS systems the control power supply draws its energy from two or more independent sources, e.g. from the mains and the battery, which, at least during mains operation, represents true redundancy.

2.7 The importance of monitoring components and functions

As already mentioned above, redundancy requires monitoring of the redundant elements. On the one hand this is necessary in order to shut down faulty branches and if necessary activate parallel paths, and on the other hand it facilitates the repair of the defective part before another part fails. Improved reliability through redundancy is only possible because of this.

In addition, however, this monitoring also prevents serious damage to components by deactivating them in time when in a critical operating state. This helps to avoid unnecessary repair times and the costs related to the repairs.

3 Reliability of systems

3.1 Parallel connection of UPS systems

UPS systems with major power ratings can usually be connected in parallel to form large groups. The main reason for this is to increase the output power. If in such a parallel group all units are required to supply the load, it is obvious that with an increasing number of UPS systems the probability of a failure increases. As can be seen in Figure 5, the MTBF value of the entire group falls as 1/n, where n represents the number of UPS systems participating in the group. With six parallel units the system has a remaining MTBF value of only 16.7 percent of the value of the individual unit and thus a failure rate which is six times higher.

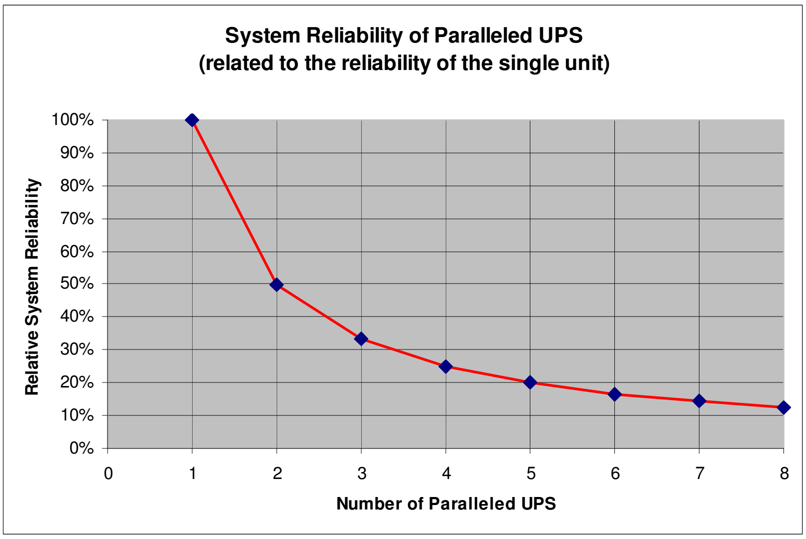


Figure 5 System reliability of power-parallel UPS units.

Instead of the parallel connection of many small units, the use of larger modules therefore represents a better solution. Referring to the ultimate configuration, this is usually the most economical variant.

The second reason for parallel connection is the introduction of a redundant component. Very often both cases are combined and represent a system of the form n+1. The redundant unit considerably increases the reliability through an increase in the MTBF value. But what equally applies here is that the reliability falls with the increasing number n of parallel units. The relationship is noticeable for the fact that the redundant unit (+1) must remain available to all remaining n units. Figure 6 figure shows a calculation up to n=7.

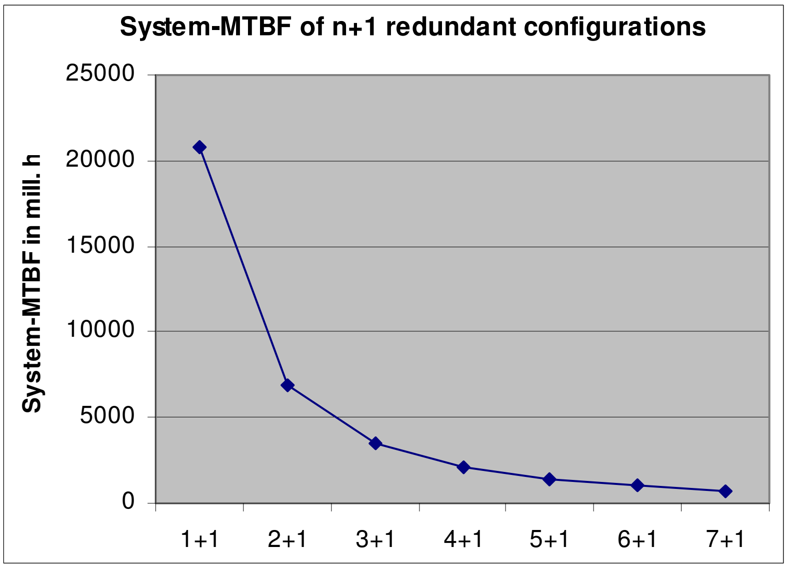


Figure 6 System reliability of redundant-parallel units.

It is therefore also true for redundant UPS systems that in relation to reliability large UPS modules are the preferred choice.

3.2 Parallel structures within UPS systems

Parallel connections are also realized within UPS systems. This is usually used to increase power. Within so-called modular UPS systems this method can also be used to achieve redundancy in case of under-utilization. Non-redundant internal parallel connections are frequently found in the power modules and capacitors of static converters to obtain the target power output of the module. In comparison, other components such as transformers and chokes, for example, can be designed for high power without the necessity of parallel connections, which has a positive effect on reliability. The same applies to electrical machines which are used in rotating UPS systems.

In the above-mentioned modular UPS systems, several individual modules can be paralleled in one housing using withdrawable unit design, to give the external appearance of one UPS system. In these systems I/O areas, and also to some extent the control and the bypass are commonly used.

The relationship illustrated above, where the reliability of the entire system falls off sharply with the number of units connected in parallel, likewise applies to each type of internal parallel connection.

3.3 Calculation of reliability figures with the aid of block diagrams

Reliability block diagrams (RBD) are a suitable method for calculating system reliability. Each block corresponds to a functional unit within a UPS or to a complete unit. Mains, batteries, switchgear, communications devices and, if necessary, transfer switches need to be included. Corresponding values for MTBF and MTTR, taken from previous calculations, manufacturer's data or out of field experience, are assigned to each block. The structure of the block diagram states which blocks must be intact so that the overall function is fulfilled. Redundancies are accounted for by parallel structures.

Two examples are described below. In the first one, shown in Figure 7, the load is shared between two units A and B, that is to say both units are required for the supply. In the associated RBD this fact is represented by a series connection of the blocks. As an AND function, both blocks must be intact so that the output is totally intact.

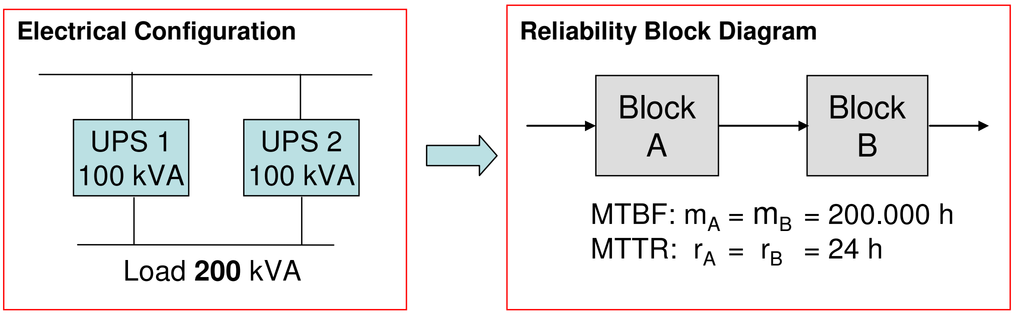


Figure 7 Schematic and reliability block diagram (RBD) of power-parallel units

The interrelationships in the entire system become clear if the time sequences of the two UPS units are represented with intact and failure times, like it is shown in Figure 8. Each failure of one individual unit causes the entire system to fail.

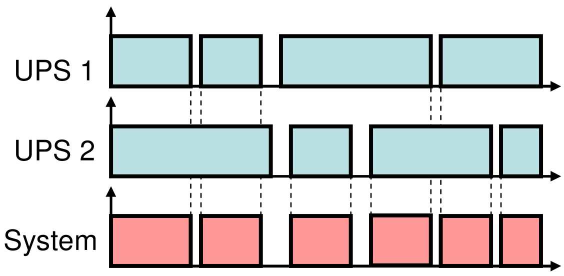


Figure 8 Effect of faults in a power-parallel configuration

The reliability values MTBF and MTTR resulting from the series connection of the blocks can be obtained using the following formulas, where m stands for MTBF and r for MTTR:

$$m_S = \frac{m_A \cdot m_B}{m_A + m_B} = 100.000\,h \tag{2}$$

$$r_S = \frac{m_A \cdot r_B + m_B \cdot r_A}{m_A + m_B} = 24\,h \tag{3}$$

This example shows that the resulting MTBF is half the MTBF value of the individual block keeping the MTTR the same.

With the redundant-parallel configuration in the second example, shown in Figure 9, one unit is sufficient to supply the load. In the RBD this is illustrated by a parallel arrangement of the blocks, which represents an OR function. If A or B is intact, then the output is intact.

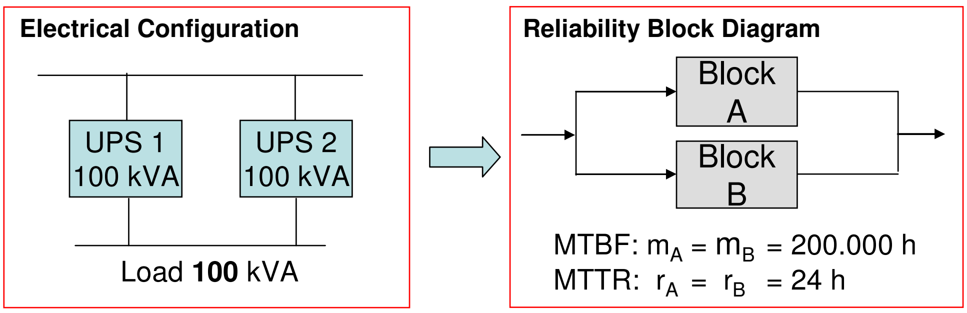


Figure 9 Schematic and reliability block diagram (RBD) of redundant-parallel units

Here again the interrelationships between the time sequences are clear (Figure 10); the exemplifying failure times of units A and B in Figure 8 and Figure 10 remaining identical.

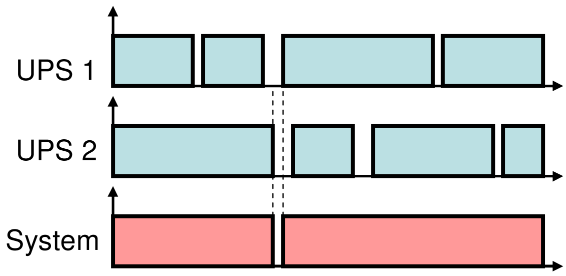


Figure 10 Effect of faults in a redundant-parallel configuration

In this case the reliability values for the system are:

$$m_{System} = \frac{m_A \cdot m_B + (m_A \cdot r_B + m_B \cdot r_A)}{r_A + r_B} = 833.000.000\,h \qquad (4)$$

$$r_{System} = \frac{r_A \cdot r_B}{r_A + r_B} = 12\,h \qquad (5)$$

This result clearly shows how great the influence of redundancies can be on the overall system.

If a block diagram contains more than two blocks, the above rules can often be appropriately combined for the parallel- and series-connected blocks and a result for the whole system can be obtained in this way. The blocks cannot be combined in the case of complex, overlapping structures. In these cases, calculation requires special software which determines the solution with the aid of Boolean algebra.

The following interesting relationship can be established with the redundant-parallel connection. In formula 4 for the system's MTBF value, compared to the first product the much smaller expression in brackets can be ignored and the formula can be reduced to:

$$m_{System} \approx \frac{m_A \cdot m_B}{r_A + r_B} \qquad (6)$$

Assuming the same reliability data $m = m_A = m_B$ and $r = r_A = r_B$ for both of the units A and B, the formula is simplified to:

$$m_{System} \approx \frac{m^2}{2 \cdot r} \qquad (7)$$

It can be deduced from this that the MTBF value of the individual redundant blocks is squared in the system reliability, i.e., a doubled MTBF value for the individual UPS results in a four times higher MTBF value for the redundant-parallel system. Figure 11 shows the system MTBF versus the MTBF of the individual unit for the 1+1 configuration.

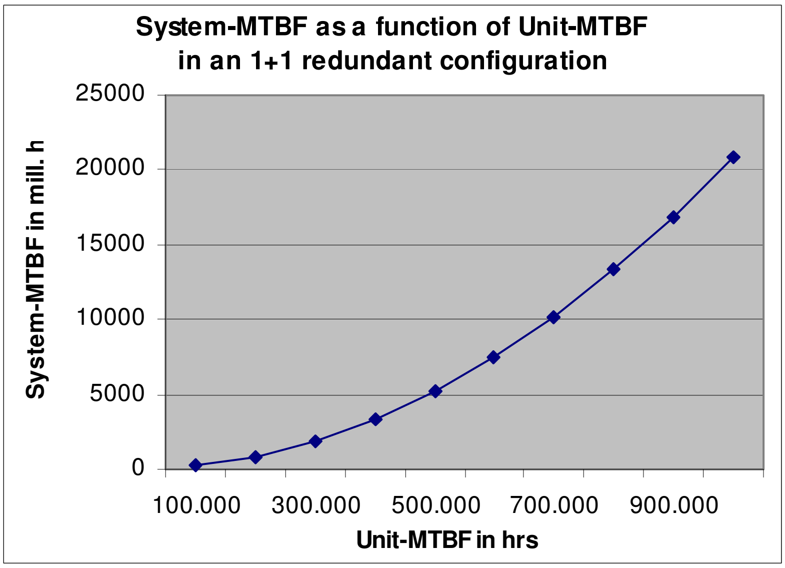


Figure 11 Dependency of the system MTBF on the unit MTBF

In comparison, the repair times (MTTR) of the units are only in a linear relationship to the system MTBF, so halving them produces a doubling of the MTBF.

3.4 Influence of common components

Calculation of the system reliability using block diagrams assumes total independency of the individual blocks. Consequently, no mutual fault influence shall occur. By comparison, in real parallel connections of UPS systems as well as inside modular UPS units, common elements, such as the communications bus between the UPS units and the common load busbar, are to be found. Added to these are possible influences between the units, which result from faults in one of the units and which can have lasting negative effects on the continued trouble-free parallel operation of the healthy units, for example through false or defective protocols on the communications bus or failure to isolate the load bus in the event of a fault.

These common elements are described as "single point of failure". They are taken into account in the block diagram by elements connected in series, as shown in Figure 12.

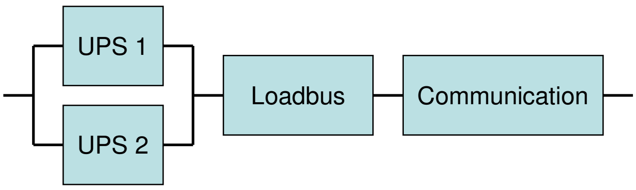


Figure 12 Common components in the reliability block diagram

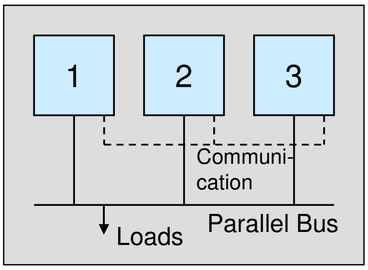
3.5 Comparison of redundant UPS configurations

In the following, the four most important configurations of redundant UPS Systems are compared to show how their reliability is affected by the MTBF values of the individual units. Table 1 gives an overview of the types of connections under consideration.

	Connection	Redundancy	Common or additional elements
1	Redundant-parallel	n+1	Communications bus, busbar
2	Isolated-redundant	n+1	Static transfer switch
3	Isolated-parallel	n+1	Power circuit-breakers, chokes
4	System-system-redundant	n+n	None

Table 1 Redundant UPS systems under consideration

The redundant-parallel connection (Figure 13) utilizing a common busbar at the output is a classic method. In the n+1 redundant system there is one more unit than would be required to supply the load. Common elements are the common busbar and the communications bus.



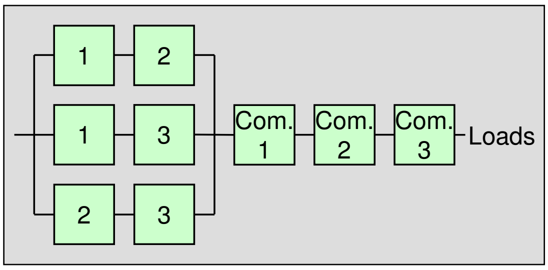
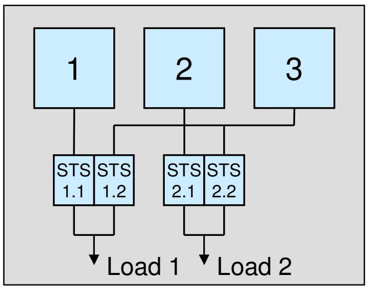


Figure 13 Circuit diagram and RBD of a Parallel Redundant UPS-System

The isolated-redundant connection (Figure 14) avoids these common elements, but additionally requires fast transfer switches (STS) which, in the event of a fault in one UPS system, connect the load to the separate redundant unit.



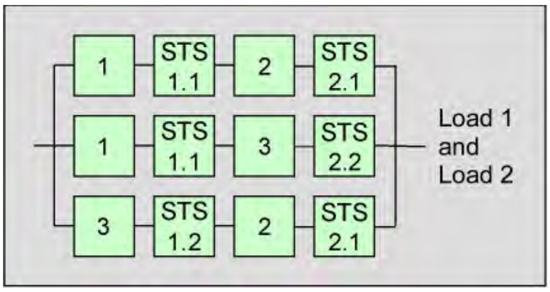
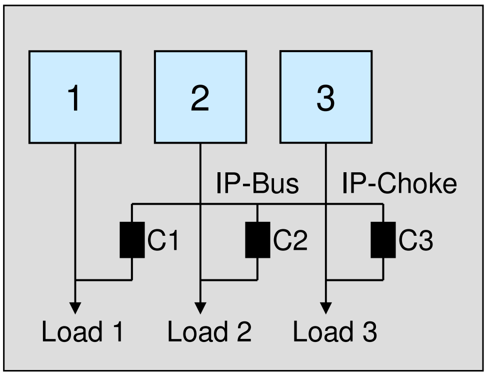


Figure 14 Circuit diagram and RBD of a Isolated Redundant UPS-System

A relatively new layout is the Isolated-Parallel System (Figure 15) consisting of independent individual units each connected to its assigned load. In this configuration the units are interconnected via chokes with virtually no interaction. All units are dimensioned so that in the event of a fault in one unit the remaining units can supply its load via the chokes (C) and the so-called IP-Bus.



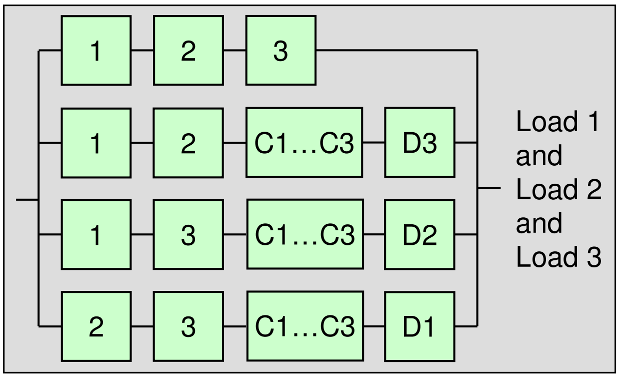
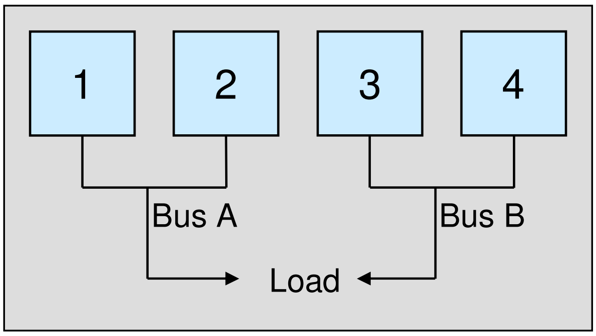


Figure 15 Circuit diagram and RBD of a Isolated Parallel UPS-System

The fourth variant represents two separate systems, each of which consists of one group of power-parallel units (Figure 16). The loads are supplied by each group via their respective busbar. There are no common elements between the two UPS groups, but the loads must be able to be connected to both supply rails without interaction, which then produces redundancy for the infeed. A typical load for this type of UPS-System are servers whose power supply units are equipped with two independent feeders.



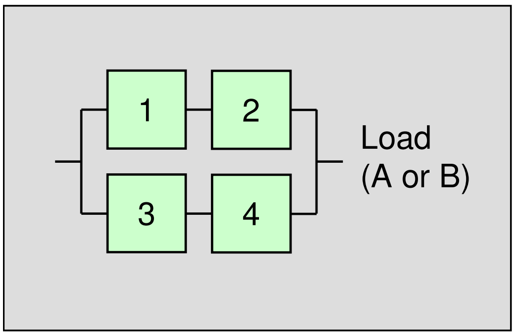


Figure 16 Circuit diagram and RBD of a System Redundant UPS-System

The following calculations show the effect of the MTBF of the individual unit on the System-MTBF of the various configurations. The assumed values in Table 2 serve as a basis for the system reliability calculations:

UPS block power		S	100	kVA
Consumer load		S	200	kVA
Repair time for all elements		MTTR	24	h
Reliability of the single unit	typical Static UPS: typical Rotary UPS:	MTBF	200.000 1.000.000	h h
Reliability of communications bus and shut-down measures		MTBF	50 Mill.	h
Reliability of static transfer switches STS		MTBF	150.000	h
Reliability of choke and shut-down measures in the isolated-parallel connection Choke Shut-down measures		 MTBF MTBF	 60 Mill. 60 Mill.	 h h

Table 2 Common data for exemplifying calculations

The layout of the redundant configurations and the associated reliability block diagram are shown in Figure 13 to Figure 16. The results are shown in Table 3.

	single unit MTBF:	200,000 h	1,000,000 h
Typ	**redundancy**	**system MTBF**	**system MTBF**
1. redundant parallel	**2+1**	**15.7 mill. h**	**16.6 mill. h**
2. isolated redundant	**2+1**	**51 mill. h**	**118 mill. h**
3. isololated parallel	**2+1**	**274 mill. h**	**6511 mill. h**
4. system-system redundant	**2+2**	**208 mill. h**	**5209 mill. h**

Table 3 Dependency of the System MTBF on the single unit MTBF.

In all configurations the results show the obvious effect of the MTBF of the individual unit on the system MTBF. Because of the common elements in the redundant-parallel system (1) the effect turns out to be less than in the systems (3) and (4), in which there are highly-reliable or even none common elements. Regarding these system configurations the above-mentioned square-law relationship which applies to independent individual elements can be seen clearly. The reliability of the rotary UPS which is 5 times higher than the one of the static units results in a system MTBF that is 25 times higher than the MTBF of the static systems.

Comparing the configurations with each other, it can be seen that the fewer the number of common elements used in a configuration, or the more reliable these common elements are, then the greater the system MTBF.

Another way to increase the reliability of an UPS system is to reduce the number of UPS units needed to supply a given load, like it is described in chapter 3.1.

The following example shows a comparison between two UPS systems, both designed to supply a load of approximately 5000 kVA.

The 1st system is designed with high power static UPS units with 800 kVA each, the 2nd system is utilising big rotary UPS with an individual output power of 1670 kVA. Both systems are realized with a redundancy of N+1 which results in a 6+1 redundant configuration for the static and a 3+1 redundant configuration for the rotary system. The MTBF values of the individual UPS are chosen accordingly to the previous example, namely 200,000 hours for the static UPS and 1,000,000 hours for the rotary UPS.

Single Unit MTBF:	200,000 h		1,000,000 h	
Configuration	Redundancy	System MTBF	Redundancy	System MTBF
1. redundant parallel	6+1	6.1 mill. h	3+1	12.5 mill. h
2. isolated redundant	6+1	7.3 mill. h	3+1	59.1 mill. h
3. isolollated parallel	6+1	39.4 mill. h	3+1	3290 mill. h
4. system redundant	6+6	23.2 mill. h	3+3	2315 mill. h

Table 4 Dependency of the System MTBF both on the number of UPS units and on the single unit MTBF

The results in Table 4 clearly show the influence of the number of UPS units on the system MTBF. Regarding the two most reliable system configurations 3 and 4 the overall system reliability of the rotary UPS system is 84 to 100 times higher than the reliability of the static ones. Compared to Table 3 all of the MTBF values in this example are decreased, which is caused by the higher number of UPS units utilized in both configurations. The significantly higher MTBF values of the rotary UPS systems are based on the much higher MTBF of the individual unit as well as on the reduced number of units needed to realize a given power demand.

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4 Summary

Reliability is the fundamental characteristic of a UPS and its importance should clearly be ranked above costs and efficiency.

The reliability of individual UPS systems depends on the reliability of a large number of components and their interaction. The use of rugged, high-performance components and a fault-tolerant control guarantees operation with low failure rates. Due to the complexity of UPS systems, high reliability should not be assumed to be self-evident, rather it requires large expenditure and appropriate experience in development and manufacturing.

A low failure rate is supported by avoidance of internal parallel connections and by minimizing the number of components. Monitoring functions for signalling faults or critical operating states reduce down-times and extend maintenance intervals. At the same time they allow the use of internal redundancies or facilitate the orderly shut-down of a defective UPS, without having a negative effect on the associated parallel group.

In evaluating the reliability of a UPS System, a distinction should be made between the frequently used term availability (A) and the fault frequency (MTBF). A high availability in conjunction with short repair times can be associated with a failure rate that is unsuitable for the application and is not acceptable to the operator of the UPS system.

The reliability of a UPS system is influenced as much by the reliability of the individual modules as by the system configuration itself. The lowest possible number of parallel units with correspondingly high power is to be preferred to a large group of smaller units. This applies equally to all power-parallel and all redundant system configurations. According to their simple design and their high power output rotary UPS are the preferred solution regarding the reliability of single UPS units as well as the reliability of big UPS systems. In addition, attention should be paid in every case to an extremely high reliability of commonly-used elements.

The considerable influence of the failure rates of the individual UPS systems on the failure rate of the system makes the reliability of the individual module a key factor in the reliability of the entire system.

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