

“DC-Grade” Reliability for UPS in Telecommunications Data Centers

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Abstract - Data Center reliability and the soaring cost of infrastructure are of major concern to businesses and Telcos. Traditionally data centers have been UPS-powered however on reliability grounds UPS are considered the “poor cousin” to their DC counterpart. This paper presents an analysis of UPS systems to show that a reliability matching DC systems is readily achievable. The paper will also discuss design options that are not required to achieve “DC-grade” reliability and which add substantially to the cost of a data center. The analysis was conducted to determine a set of configurations for use in a national standard by a leading Australian Telco. Configurations graded according to reliability enable a value comparison to be made between different UPS systems. A detailed reliability assessment was made of each configuration using Monte Carlo power system reliability modeling software.

Traditionally DC telepower systems have been the cornerstone of reliable telecommunications power. As telecommunications advances rapidly towards an IP-centric network, the role and importance of Data Centers in telecommunications has surged. Data Centers however are traditionally AC powered and accordingly the importance of UPS systems to Telcos has increased dramatically. Emerging telecommunications platforms do not always have a DC powering option therefore highly-dependable UPS systems are needed. The problem is that UPS systems typically provide an order of magnitude lower reliability. High-end DC systems can readily attain an MTBF of 200+ years while UPS systems typically achieve as little as ~10-30 years MTBF. With the cost of modern data centers soaring, the paper will show how such costs can be contained while designing UPS systems with “DC-grade” reliability.

I. INTRODUCTION

In 1993, a large Australian telecommunications carrier commissioned a project to develop a performance standard for DC systems. This was a direct result of dissatisfaction with the performance being obtained with large centralized DC systems. Typical MTBFs of “high-end” DC systems at the time were around 50 years (40 major outages annually). The performance standard recommended distributed DC systems with A-B redundant planes. Following the introduction of these systems actual field reliability rose to between 200 and 400 years MTBF as evidenced by Figure 1. This produced a reduction in the number of annual major outages by up to 8 times.

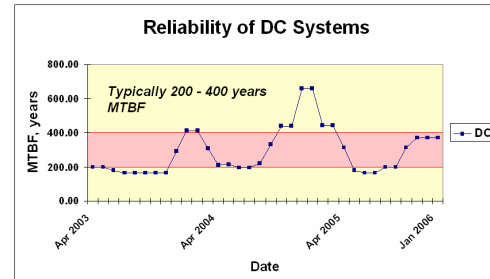


Figure 1: Reliability of “high-end” telecom DC systems*

“DC-Grade” can thus be defined as an MTBF of ≥ 200 years.

“DC-Grade” Reliability \Leftrightarrow MTBF ≥ 200 system years

By contrast, typical reliabilities of UPS systems over the same period are illustrated in Figure 2.

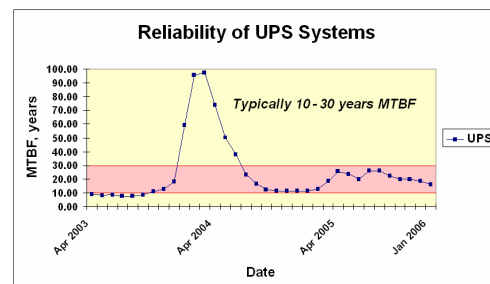


Figure 2: Reliability of “high-end” telecom UPS systems*

*The excursions in Figures 1 & 2 are not significant and are commonly observed in highly-dependable systems.

More recently, a project was commissioned by the same Telco to review existing AC no-break and data center performance standards. The project included a review of standards, practices and whitepapers locally and internationally. It was found there was a need to define the reliability of UPS system configurations in a way that could be used to provide cost-effective solutions.

A review of existing data center standards has shown that emphasis is on power supply *availability* rather than reliability. Consequently these standards do not enumerate the qualities a system should have to maximize *MTBF*. Attaining “DC-grade” reliability is about ensuring a power system can deliver a predictably low rate of power outages.

Consequently work was undertaken to model a variety of UPS systems to derive the principles needed to ensure “DC-grade” reliability could be consistently achieved.

II. RELIABILITY DEFINITIONS

The reliability referred to in this paper is that delivered by the power system – excluding the reliability of the critical load.

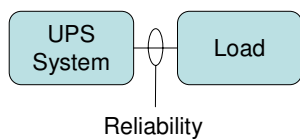


Figure 3: Power reliability excludes critical load

Two commonly used metrics to express the “reliability” of a repairable system is Availability and MTBF. The reliability of a system experiencing exponentially distributed failures is given by

$$R(t) = e^{-t/MTBF} \quad - (1)$$

Where

t = time,
R(t) = reliability,
MTBF = mean time between failures

$$MTBF = \text{system operating time} / \text{num failures} \quad - (2)$$

Availability is given by:

$$Av = (MTBF - MTTR) / MTBF \quad - (3)$$

Where MTTR = mean time to repair

A. Availability & MTBF

Availability is not a good performance metric for DC and AC power systems. Knowing the availability of a system does not provide any information about the likely frequency of outages from that system. The frequency of outages is the most useful distinguishing feature when comparing power systems. Availability is a dimensionless quantity. MTBF provides information about the likely frequency of outages to expect from a system.

Availability is sometimes quoted for UPS equipment and in performance specifications cited by data centre operators.

As with telecommunications networks, availability is commonly used to define the performance of key data centre components such as servers. As a performance measure for power systems, availability is not an appropriate measure as will be illustrated in this paper.

System availability is often used because it is easier to calculate than MTBF. To estimate system MTBF, for anything other than the simplest of power systems, it is necessary to use Monte Carlo simulation. With appropriate software, MTBF can be readily estimated as described in the following.

III. METHODOLOGY

A. Monte-Carlo Simulation

Other than for very simple systems, it is not feasible to manually calculate the reliability of UPS systems. To overcome this difficulty a methodology known as Monte Carlo simulation is used. There are a variety of software packages available that can accomplish this through reliability block-diagrams. For the analysis in this paper, a software program known as Analyst¹ was used because it enables complex systems to be analyzed from a single-line electrical diagram. Single line diagrams are easier to work with than block diagrams and require fewer skills thereby making the evaluation of complex systems easier.

Analyst has been independently verified by the former Telstra Research Laboratories². The modeling accuracy is high because the software can take into account complex logic and time-varying elements such as battery reserve (even under changing load conditions) to produce a true estimate of reliability.

The colored electrical schematics shown throughout this paper are actual working simulation models that were taken directly from the Analyst software.

B. Overview of Simulation Method

To carry out a reliability analysis, a one line diagram of the system is drawn. A simple dc system is illustrated in figure 4.

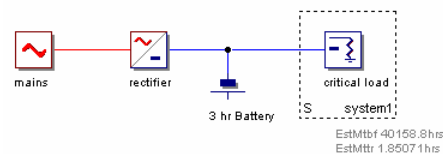


Figure 4 – Simple System

The electrical and statistical properties of each component are entered such as current rating, battery capacity, MTBF, MTTR, etc. The dotted rectangular component in Figure 1 represents the critical system under study. Once the single-line diagram is complete, the software permits a visual verification of the model. Once the model is verified, the software calculates the system reliability.

C. Failure Rates

Table I contains the general failure rates used in the modeling.

TABLE I
FAILURE RATES USED IN THE MODELING

Component	MTBF hrs	MTTR hrs	Source
“High Quality” Mains	8.03×10^3	Weibull $\eta = 0.02$ $\beta = 0.25$	C2-1 ³
Generator start rate 0.9875	2×10^3 (running)	4	C2-1 ³
Switchboard	4.38×10^6	9	C2-1 ³
Circuit Breaker	1×10^6	2	C2-1 ³
ATS (main inputs – generator/mains c/o)	5×10^5 – 1×10^6	2	as per CB
3 phase Static Switch	5×10^5	2	Median value from vendor estimates
3 phase Rectifier	2×10^4	2	C2-1 ³
3 phase Inverter	2×10^4	2	C2-1 ³
Battery	1×10^6	8	C2-1 ³
Failure of UPS to switch to battery drive 0.1%, combines battery o/c, battery cb left open, etc.			Cisco Whitepaper, Gordon Associates Raleigh NC

D. Verification of Base Simulation Model

To ensure the modeling was representative of the real world situation, a base level UPS system model was compared against actual failures observed in the field⁴. The base simulation model is shown in Figure 5.

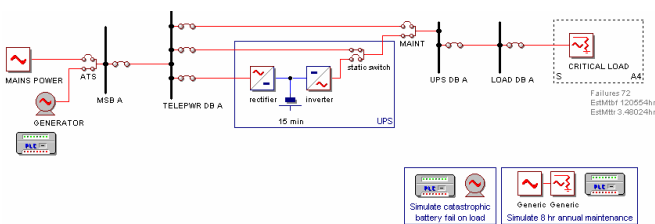


Figure 5 – Model of Standard UPS

There were a total of 72 UPS outages recorded in the field outages database for a particular Telco. These outages were examined and a count of failure modes was extracted. The simulation model was operated until 72 service disruptions were obtained to determine the spread of failure modes. The results of modeling and actual field failures are shown in Table II.

TABLE II

DISTRIBUTION OF FAILURE MODES

Failure Mode	Field Data	Simulation
AC supply dist fault	29.2%	29%
generator fail	5.6%	2.8%
battery fault	15.3%	12.5%
mains fail during maintenance	4.2%	0%
UPS equipment	27.8%	28%
UPS ac dist	18.1%	28%

As Illustrated in Table II, the spread and number of failure modes obtained from modeling shows good correlation to actual field failures. The key difference is that simulation appears to over-estimate the number of failures associated with the AC distribution between the UPS and load. The simulation model was not corrected as it is believed that field failures arising from feeder faults and inadvertent switching of servers is under-reported in the failure data.

An approximate “rule of thumb” for the spread of failures in UPS systems is depicted in Figure 6.

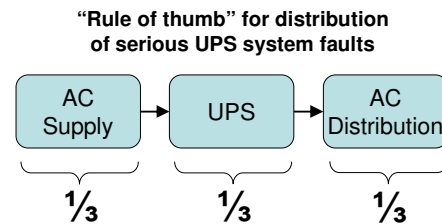



Figure 6 – Source of outages in a UPS system

E. Human Error

The modeling conducted takes into account the effects of human error to a first approximation. This is because the base model was validated against field results that include interruptions from all sources including human error. While it is generally not possible to build a model to predict human error, it is feasible to model human error if outage statistics are known. The model itself simply represents human error as an interruption of power.

IV. MODELING RESULTS

Modeling was conducted in two stages. First the energy sources (mains, generator & battery) were modeled in isolation to determine the minimum configuration needed to deliver MTBFs in excess of 200 years. The second stage involved the modeling of a number of common UPS configurations. This also involved a qualitative investigation of design options required to achieve “DC-grade” reliability and those considered unnecessary.

NOTE: In each model the symbol  refers either to an electro-mechanical changeover switch, or static switch as marked. This is because the simulation software uses the same component (symbol) to perform both functions.

A. Stage 1 - Energy Sources

Energy sources were modeled in isolation to determine the minimum configuration needed to satisfy system MTBFs of 200+ years. The statistical parameters of each energy source are shown in Table I. The simulation model is shown in Figure 7. Rectifier and inverter components were set to be perfect (no failures) in the modeling to assess the reliability of energy sources acting through a perfect power conversion chain. The results of modeling are shown in Table III

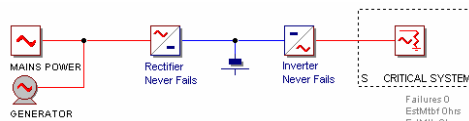


Figure 7 – Simulation Model for Energy Sources

TABLE III

ESTIMATED RELIABILITY OF ENERGY SOURCES

Mains Feeders	Battery Reserve	Num Generators	MTBF, yrs	MTTR, hrs	Av, %
1	15 mins	N+1,N=1	>1,000	2.5	8 nines
1	15 mins	N,N=1	450	2.8	6 nines
1	15 mins	N,N=2	240	2.7	6 nines
1	15 mins	N,N=3	160	2.9	5½ nines

If the UPS system is to deliver an MTBF of 200 years, then the reliability from energy sources acting alone must be well in excess of 200 years MTBF. The row meeting this criterion is shaded in Table III. The row below with single generator also has an MTBF exceeding 200 years but was omitted on the basis of a sensitivity analysis. The results suggest that the minimum for “DC-grade” reliability is single mains feeder, N+1 gensets and 15 minutes reserve. There are of course other combinations of energy sources that will deliver high MTBF but the selection made here is considered a practical balance.

It is possible to continue to add more redundancy in energy supplies including redundant mains feeder/substation, longer battery reserve and a dual set of redundant generators. This may be necessary if failure rates (energy sources) are much lower than used here but is unlikely.

B. Stage 2 - UPS Systems

A range of common UPS configurations were modeled. There are a multitude of other possible configurations but those selected here are commonly used.

Figure 8 shows a system without a UPS. This configuration was included to help clarify why availability is a poor measure of power system performance. Despite having no UPS, the availability of this configuration is as

good as or better than UPS configurations in Figures 9,10,11,12 and 13. However, the MTBF is only 0.9 years! This illustrates why availability is not an appropriate measure of power system performance.

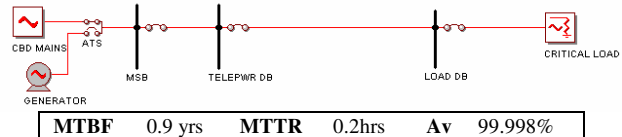


Figure 8 - High-Quality Mains with Generator & ATS changeover

Figure 9 shows the model for a single UPS system with a common AC input shared by both the rectifier and static bypass feeding a single-cord load.

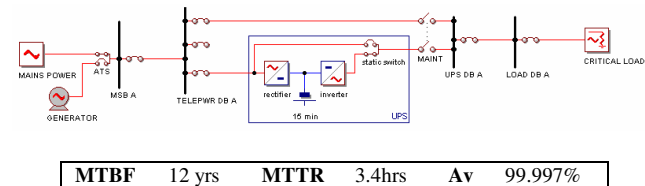


Figure 9 - Single UPS, common AC supply, Single-Cord Load

The UPS model in Figure 10 has a separate AC feed for the static bypass.

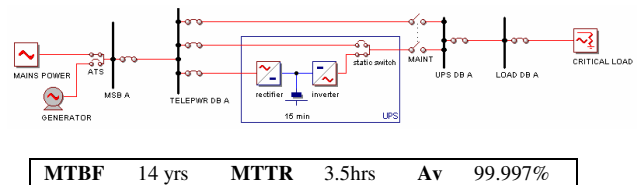


Figure 10 - Single UPS, separate AC bypass supply, Single-Cord Load

The UPS model in Figure 11 has two battery strings.

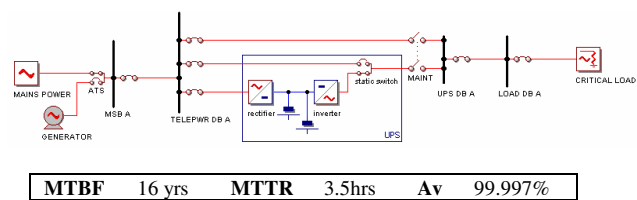
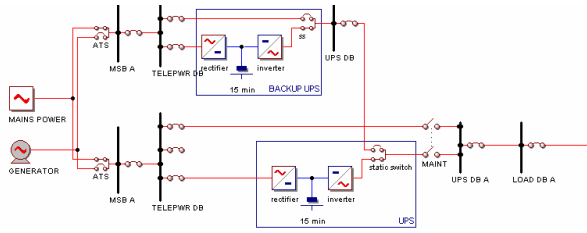


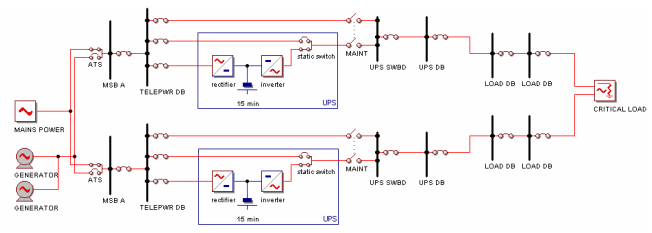
Figure 11 - Single UPS, Twin batteries, Single-Cord Load

Figure 12 shows the model of a UPS system with static bypass to a second UPS system – commonly referred to as a “catcher” system.



MTBF 23 yrs **MTTR** 3.6hrs **Av** 99.998%

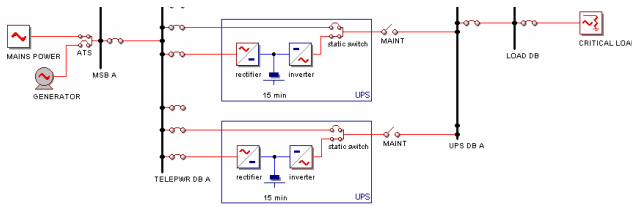
Figure 12 - "Catcher" System – UPS bypass to UPS, Single-Cord Load



MTBF >1,000 yrs **MTTR** 0.36hrs **Av** 99.999995%

Figure 16 - 2N UPS, N+1 Generator, Dual-Cord Load

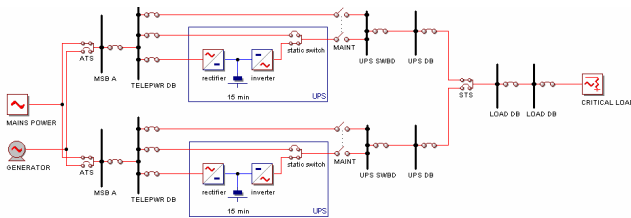
Figure 13 shows the model of an N+1 UPS system.



MTBF 24 yrs **MTTR** 3.8hrs **Av** 99.998%

Figure 13 - N+1 UPS, N=1, Single-Cord Load

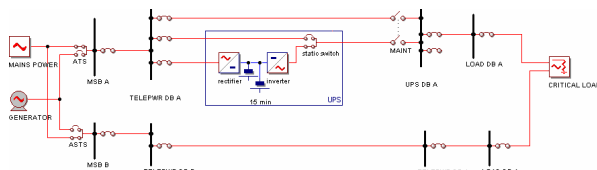
The STS in Figure 14 was modeled as a high-quality device with an MTBF of 10^6 hrs.



MTBF 31 yrs **MTTR** 3.5hrs **Av** 99.999%

Figure 14 - 2N UPS, STS, Single-Cord Load

Figure 15 is a model of a dual cord system with conditioned UPS on one cord and a mains feed to the second cord.



MTBF 270 yrs **MTTR** 1.9hrs **Av** 99.99992%

Figure 15 - Single UPS, Redundant Mains Feeding, Dual-Cord Load

V. DISCUSSION

The results of modeling are discussed along with qualitative considerations of key areas that establish the minimum sufficiency for "DC-grade" reliability.

A. "DC-Grade" UPS System

The system described in Figure 17 provides "DC-grade" reliability but at substantially reduced cost compared to "Tier 4" systems described in TIA 942⁵. The key principles for maximizing system MTBF to achieve "DC-grade" reliability have been annotated throughout Figure 17 and are discussed in the following.

B. Longer Battery Reserve?

Unlike DC systems which have the battery hard-connected to the load with no conversion, UPS systems have an inverter to convert back to AC in addition to the distribution elements. It follows that the impact of increased battery reserve is not as pronounced in UPS systems. This is borne out by the modeling that was carried out. A number of single UPS systems were modeled with the only change being the battery reserve. The results are shown in Table IV.

A second reason why increasing UPS battery reserves may not be indicated is when the thermal equipment room reserve either approaches, or is less than the UPS battery reserve. Given the rapidly increasing energy density of server racks in data centers this will become normal. When the loading in racks exceeds 10 kW the consequent thermal reserves can be measured in tens of seconds rather than minutes. This makes it un-necessary to have long UPS battery reserves (given the UPS powers only the critical load).

TABLE IV

EFFECT OF BATTERY RESERVE ON SINGLE UPS RELIABILITY

Battery Reserve	MTBF, yrs	MTTR, hrs	Av, %
15 mins	14.8	3.6	99.997
30 mins	15.9	3.6	99.997
60 mins	16.3	3.5	99.998
3 hrs	20.3	3.7	99.998

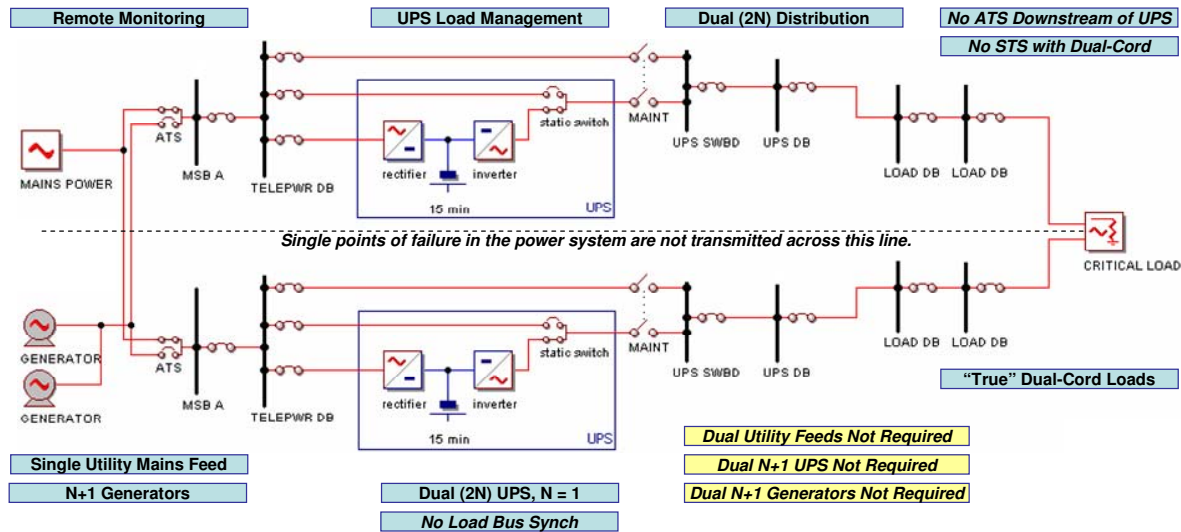


Figure 17 – “DC-Grade” UPS System

C. ATS (Automatic Transfer Switch)

An ATS is an electro-mechanical device often incorporating circuit breakers that can automatically transfer the load between two sources. Large 3-phase varieties are invariably “slight-break” and impose a break to the critical load if required to transfer on load.

ATS are typically used in the interest of maximizing availability – which they can certainly do. In order to maximize MTBF, ATS should not be used in the critical no-break path downstream of a UPS. This is illustrated by the following models that show a system with high-quality ATS has a higher availability but lower MTBF.

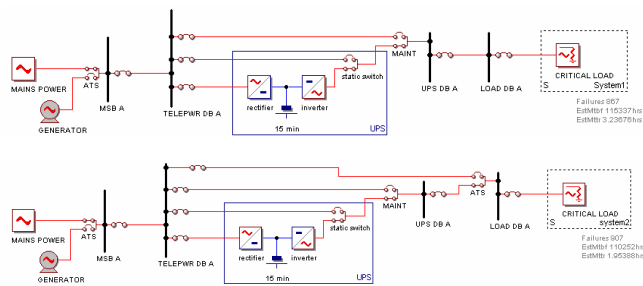


Figure 18 – UPS Models with and without ATS

TABLE V

RESULTS OF MODELING WITH AND WITHOUT ATS

System	Description	MTBF, yrs	MTTR, hrs	Av, %
System1	No ATS	13.2	3.2	99.997
System2	High Quality ATS	12.6	2.0	99.998
System2	Low Quality ATS	9.5	2.2	99.997

D. STS (Static Transfer Switch)

STS are typically employed to power single cord loads from a dual-source system. Topologically they appear similar to systems with dual-cord loads. In practice however true dual cord loads provide vastly better reliability. This was established by comparing the model of an STS with a dual cord load.

If we were to strip away all the paraphernalia to examine the very best reliability a dual-cord load and an STS powering a single-cord load could offer, we would have the situation depicted in Figure 19. The two rectifiers making up the dual cord load have an MTBF of 10,000 hours. The STS has an MTBF of 1,000,000 hours.

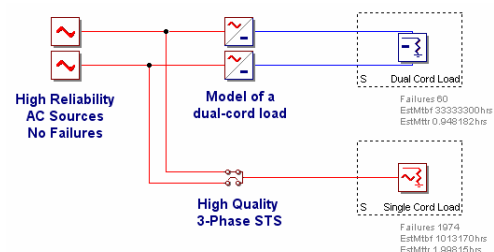


Figure 19 – Model of a Dual-Cord Load & STS

This modeling shows the reliability of a dual-cord load is approximately 30 times higher than a high-quality 3-phase STS. In reality the situation is much worse since there are always some AC distribution elements such as switchboards and circuit breakers. These have been added in to obtain the model shown in Figure 20.

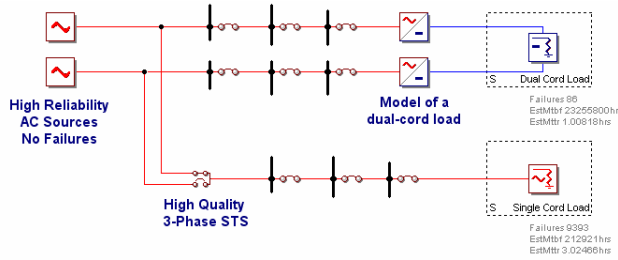


Figure 20 – Model of a Dual-Cord Load & STS with distribution elements

Now, the reliability of the 3-phase STS system with single cord load is more than 100 times less than the dual cord load system having an equal segment of distribution.

A number of conclusions can be drawn from this:

- (1) The best possible reliability of a 3-phase STS powering a single cord load is considerably lower than a system with dual cord load.
- (2) The best possible reliability attainable from a 3-phase STS powering a single-cord load is well short of “DC-grade” and is typically 20-40 years MTBF.
- (3) Without the use of application-layer redundancy (i.e. redundancy on the server application, clustering, failover, etc), it is difficult to achieve “DC-grade” reliabilities with single cord loads in UPS systems.

The preceding discussion has been undertaken without regard to a number of other factors that negatively influence the reliability of STS. These include synchronization requirements of sources, out of synch transfer settings, downstream fault handling and cross-source fault transfer protection, effect of fast slight-break transfers on loads with magnetics (e.g. motors, transformers). All of these considerations will work to further degrade the reliability of STS in single cord systems in comparison to a system with dual cord loads.

Single-phase rack-mounted STS are often used when single-cord loads are to be deployed in a dual distribution system. These devices may be static but are often just a simple relay type that provide fast no-break changeover. Being close to the critical load means that the size of the common point of failure (the single output feed) is kept relatively small. Also, the reliability of a relay type changeover is generally much higher than a solid-state unit since it is much simpler. A disadvantage of relay type units is that fault handling is usually not provided. A fault in the load can trip the upstream device serving one side. The STS will then transfer to the second source attempting to keep the load powered only to trip the upstream device serving the second side. This is a mechanism that is generally not present in properly designed dual cord loads.

E. Standby Generators

As illustrated in Table III, the MTBF of energy sources is high enough for “DC-grade” reliability when N+1 generators are used. The data used for the generator good-start ratio came from approximately 20,000 start attempts in the field. The field data for generator starting reliability was sourced from telecommunications applications in which the generators are regularly tested. A sensitivity analysis was performed by reducing the starting reliability of the generators by a factor of 3. The resultant energy system continued to return an MTBF well in excess of 1,000 years. Dual N+1 generators were not required to achieve “DC-grade” reliability.

F. Mains Utility Feeders

Referring to Table III, the MTBF of energy sources is high enough for “DC-grade” reliability when a single, high quality mains feeder is used. The mains feeder MTBF is that obtained for feeders used in telecommunications buildings in central city locations. A sensitivity analysis was performed by reducing the mains feeder reliability by a third. The resultant energy system continued to return an MTBF well in excess of 1,000 years and remains more than adequate to support “DC-grade” reliability.

The modeling illustrates that dual-redundant mains feeders are not required to obtain “DC-grade” reliability.

The provision of a second utility substation is an expensive undertaking. Unless the second feeder can be considered “relatively” independent to the first, it will not substantially alter the reliability of the incoming mains. Independence means that it must be sourced from a different part of the utility grid. Even if this can be done, as the foregoing discussion has shown, a second feeder is generally unnecessary from a reliability perspective. A parallel system of generators by contrast can be considered an independent source.

G. Single and Dual Cord Loads

A dual-cord load is one which can be supplied from two, independent sources of power. Provided at least one of the two sources is always present, then the load will function normally. By contrast a single cord load has only one power lead.

In practice there are variations of what constitutes “dual cord”. For the purposes of the current work, dual cord requires the existence of two AC to DC power supplies in each server, such that the two AC sources do not require to be synchronized and can operate independently. The server must be able to operate normally if either source is unavailable.

H. 2N UPS

The “DC-grade” system shown in Figure 17 uses a single UPS on each side. The use of N+1 UPS on each side is not required to obtain “DC-grade” reliability. For maintainability, normal maintenance bypass switching for each UPS is sufficient. Each half can be switched to

maintenance bypass for long periods of time without appreciably changing the system reliability. This is evidenced by considering the model shown in Figure 15 which still achieves “DC-grade” reliability with a mains source on the second cord.

I. UPS Load Management

The management of load on UPS systems has become a vital but complex undertaking in recent years. The error in calculating true loading on a UPS can exceed 40% in some cases. Table VI lists actual de-ratings of leading brand UPS from around the world as supplied by vendors.

TABLE VI
DE-RATING OF UPS AT 0.8 LEADING POWER FACTOR, 40 °C, VARIOUS RATINGS FROM 30 KVA TO >500 KVA

Manufacturer	Type	De-rated Capacity
A	1	74%
	2	71%
	3	89%
B	1	100%
C	1	64%
	2	71%
D	1	68%
	2	71%
E	1	64%
	2	79%
F	1	95%

Today leading power factors are commonly found at data centers due to relatively recent changes in international standards for OEM embedded power supplies.

Most UPS self-protect on over-load but not always. There are also other reasons why overloads can lead to outages of UPS systems. An overload can result in time spent in bypass or inadvertent loss of redundancy in parallel and 2N systems. One client experienced 6 outages of UPS systems related to overload over a period of time. When a load management system was introduced, this dropped to only one outage in a similar period.

A full and proper UPS load management system is essential if “DC-grade” reliability is to be maintained. It is noted that full de-rating information is generally difficult to obtain from vendors for obvious reasons.

Data center loads are becoming more dynamic due to efforts to improve energy efficiency. Servers are able to control their power consumption through idle power-down. Loads can be connected in an ad-hoc manner without appropriate change management. Due to these issues, UPS loads must be monitored continuously to ensure “DC-grade” reliability is achieved. Remote monitoring is considered an essential requirement to provide effective load management.

VI. CONCLUSION

Today’s UPS systems are capable of delivering DC-grade reliability if certain system-level design principles are observed.

Cost pressures on data centers have risen in part due to excessive demands for duplication and redundancy in utility feeds, generators and UPS systems. This paper has shown that such demands are not required to achieve the highest levels of reliability matching DC systems. Some existing data center standards call for levels of redundancy and duplication on a massive scale. According to the current work, such levels are considered difficult to justify on reliability grounds.

There is little doubt that operational pressures attendant in managing and growing Data Centers will constitute a challenge to achieving and maintaining “DC-grade” reliability. It has been variously reported that 50% of the world’s data centers will run out of power and cooling by 2008 due to rapid growth and increasing heat densities.

The importance of dual redundant plane systems (e.g. dual-cord) is well understood in telecommunications and has been in use for many years. While there is considerable rigor around the reliability of telecommunications switches, the same rigor is not always present in server technology where “dual-cord” can mean many things. Care must be exercised if the goal of “DC-grade” reliability is to be reached.

It has been shown that “DC-grade” reliability in UPS systems is achievable.

ACKNOWLEDGMENT

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