Comparing Availability of Various Rack Power Redundancy Configurations

By Victor Avelar

White Paper #48

Executive Summary

Transfer switches and dual-path power distribution to IT equipment are used to enhance the availability of computing systems. Statistical availability analysis techniques suggest large differences in availability are expected between the various methods commonly employed. This paper examines various electrical architectures for redundancy that are implemented in today's mission-critical environments. The availability analyses of these various scenarios are then performed and the results are presented. The analysis identifies which approach provides the best overall performance, and how alternatives compare in performance and value.

Introduction

Equipment with redundant power supplies is also referred to as dual-corded equipment, having redundant power supplies, each with its own cord. The use of dual-corded equipment is a "best practice" that helps maintain optimal power availability for the IT equipment and provides the necessary redundancy to prevent downtime from a single failure within the power distribution system. This added redundancy also facilitates power system maintenance. Unfortunately, the majority of today's mission critical environments do not fully benefit from this best practice. This paper presents various electrical architecture scenarios that may be implemented in today's data center. The availability analyses of these various scenarios are then performed and the results are presented.

Approaches to Distributing Power to Racks

The following illustrations provide an overview of various approaches for increasing availability to rack-mounted equipment but can also be applied to stand-alone equipment as well. The different approaches are typically selected with the objective of achieving a desired level of availability, with the more costly approaches presumably providing a higher level of availability. **Figures 1** and **2** show how power is often distributed within a data center rack today.

***Figure 1** – Typical rack-mount power*

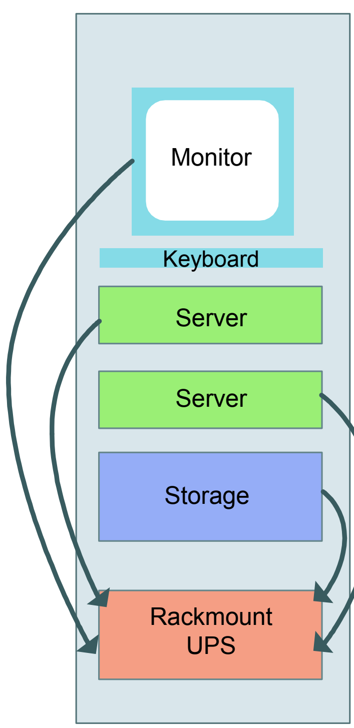


***Figure 2** – Typical centralized power*

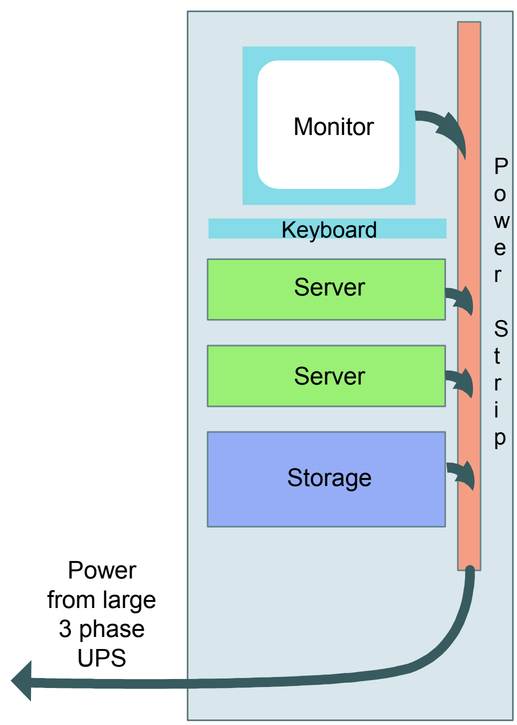


Figure 1 shows a typical rack power distribution configuration used in small or medium size data centers and wiring closets. This configuration allows for easily moved racks with internal UPS battery backup and surge protection. In data centers where dozens or hundreds of racks are used, **Figure 2** with a large centralized UPS is a more common configuration. There is no power redundancy in the power distribution to the rack in either case.

Other electrical architectures use devices to switch from a primary power source to a secondary power source. Two such devices are a Static Transfer Switch (STS) and an Automatic Transfer Switch (ATS). Both of these units range in size from about 1kW to over 1MW. These devices are discussed in detail in APC White Paper #62: “Powering Single Corded Equipment in a Dual Path Environment”. Examples of both of these switches are shown below.

Rack-mount 3-Phase 6kVA ATS

3-Phase 300kVA STS

Figures 3 and **4** demonstrate how power is sometimes distributed in large, mission critical facilities. In both cases there are two redundant paths leading to an STS, however the utility sources feeding the UPS may or may not be redundant, depending on factors such as cost and substation availability from the utility company. The only difference between the two scenarios is that **Figure 3** uses a single transformer downstream of the static switch while **Figure 4** uses redundant transformers upstream of the static switch. However, in both cases, the STS, downstream subpanel, and associated wiring are potential single points of failure. These methods provide some redundancy, but the remaining components that have no redundancy present failure risk hazards and potential maintenance difficulty.

***Figure 3** – Redundancy to the load with STS*

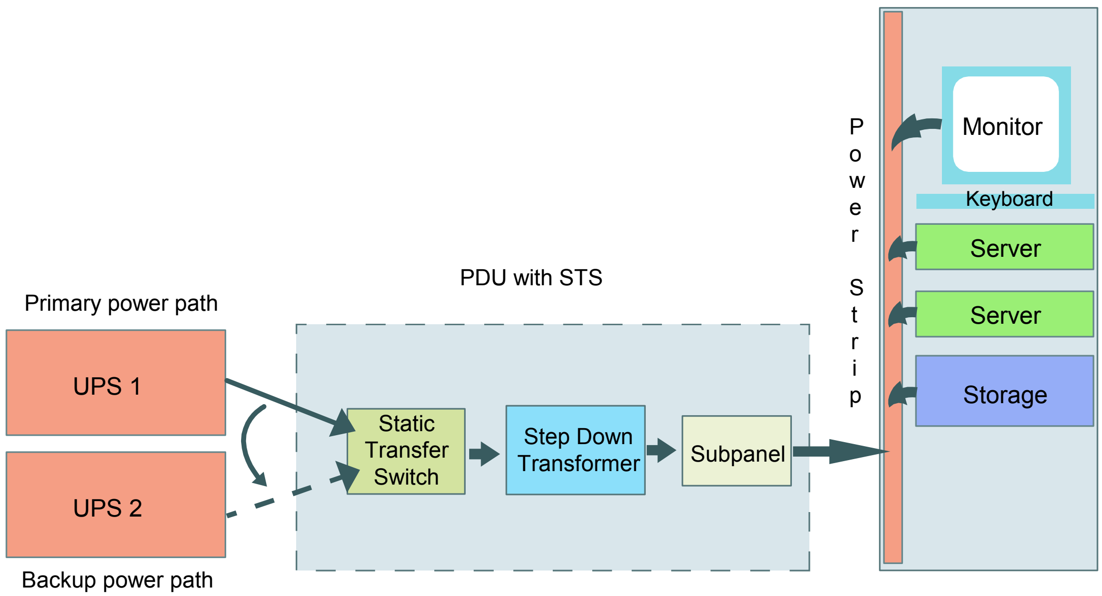
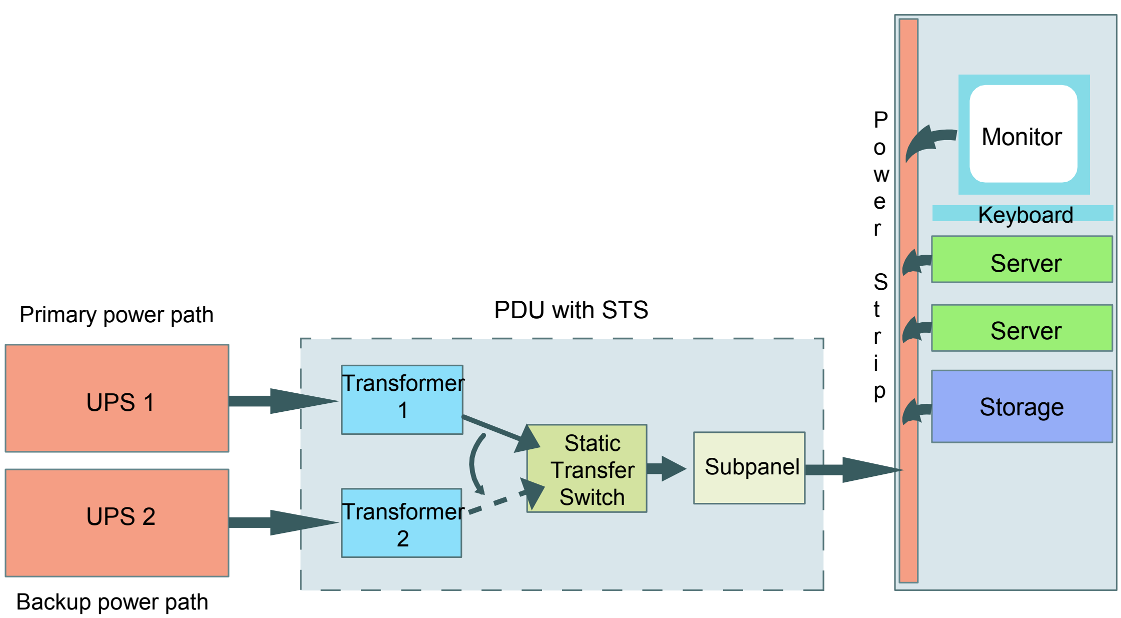


***Figure 4** – Redundancy to the load with STS (redundant transformers)*



Figures 3 and **4** are an improvement over the data center configurations shown in **Figures 1** and **2**, but they still do not offer full redundancy to the rack. Although a redundant UPS and transformer are added, the static switch, subpanel and their associated wiring are single points of failure.

Figure 5 addresses the single points of failure limitation found in **Figures 3** and **4** by pushing redundancy towards the load. This solution removes the STS and adds an extra subpanel thereby pushing the redundancy benefits closer to the load by means of a Rack Automatic Transfer Switch (ATS). Any maintenance upstream of the Rack ATS can now be completed without taking down the load. Although this scenario exhibits fewer non-redundant components than that of **Figures 3** and **4**, the Rack ATS remains a single point of failure, as does the equipment's own power supply.

***Figure 5** – Redundancy to the load with Rack ATS*

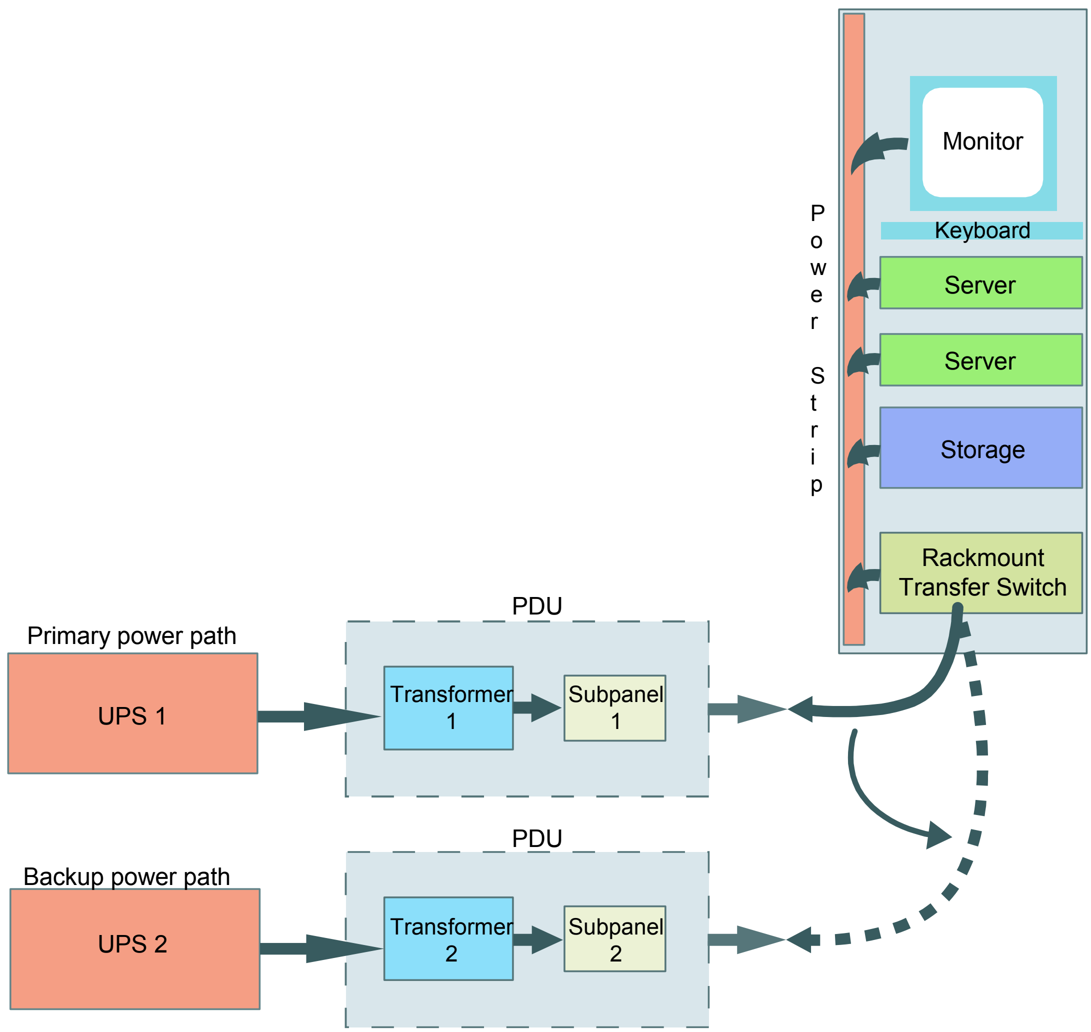
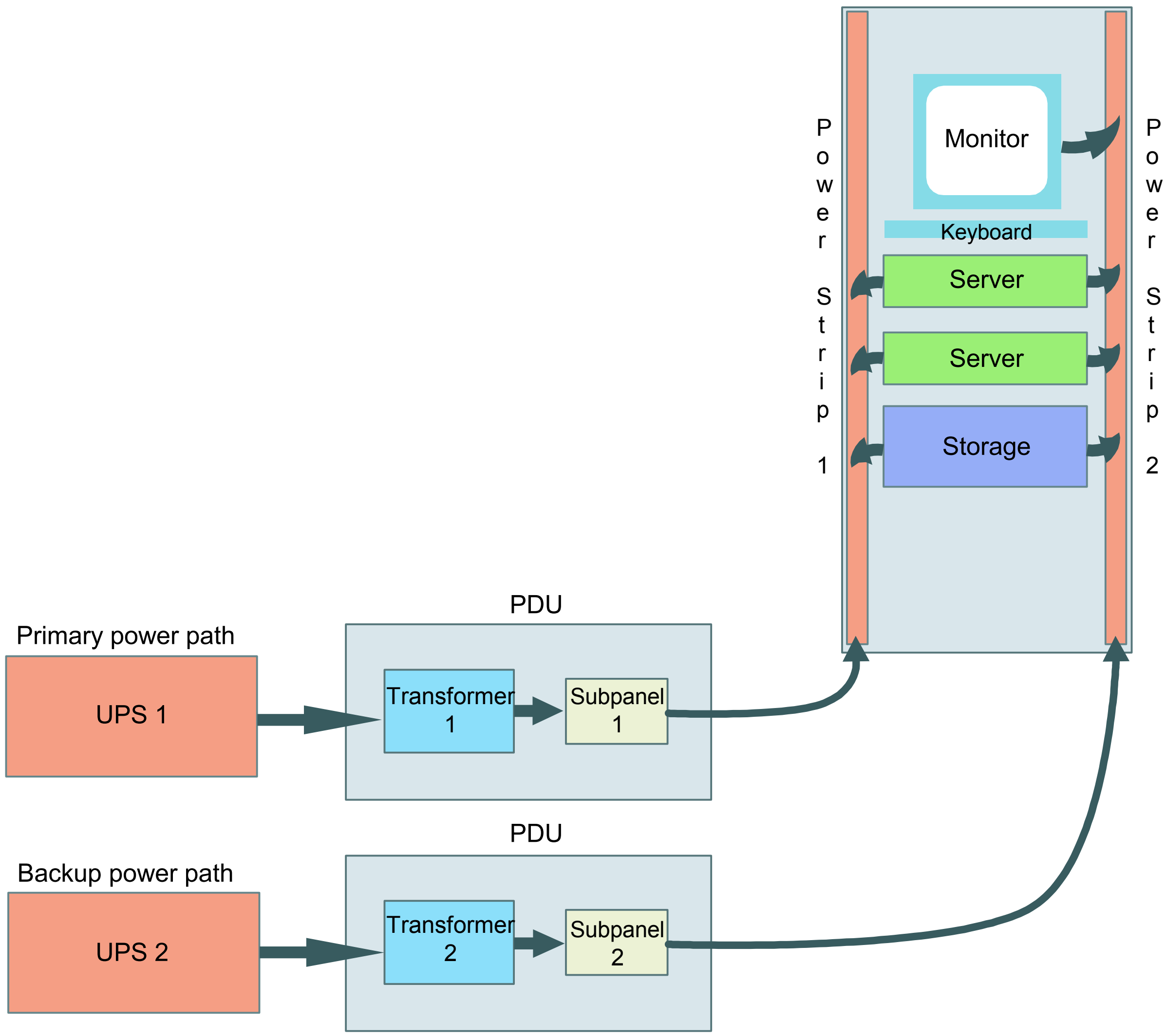


Figure 6 shows how full redundancy to the load can be achieved using dual-corded equipment with redundant power supplies. This scenario has two important changes to **Figure 5**: the Rack ATS is taken out, and dual-corded equipment is used. Full redundancy is now brought straight through to the load. Notice also that an extra power strip is used to maintain redundancy. This solution is highly available

compared to those discussed thus far; however, it is also the most expensive solution and can only be used with dual corded equipment expressly designed for this use.

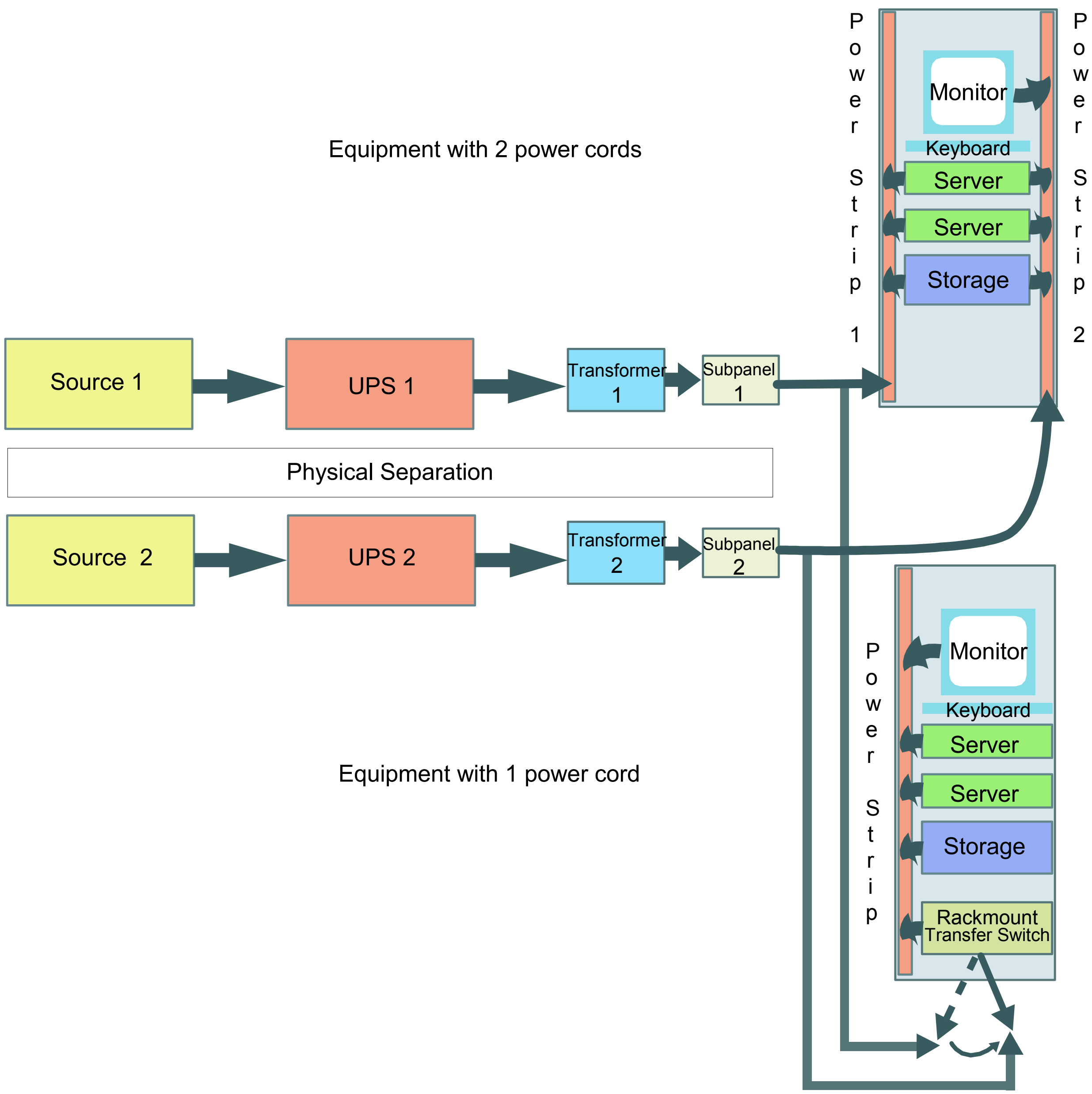
Figure 6 *– Redundancy to the load with dual-corded equipment*



The architecture in **Figure 7** combines the architectures of **Figures 5** and **6**, and shows an alternate solution that accommodates both single and dual-corded loads. This solution employs a hybrid combination of previously reviewed designs. Full power redundancy is maintained for the dual-corded computer equipment. For the single-corded equipment, redundancy is maintained up to the Rack ATS, however, the switch and equipment power supplies are now single points of failure.

Figure 7 also shows added physical separation. This is often referred to as "compartmentalization," where various subsystems within the power distribution and backup system are physically separated. Physical separation, if implemented properly, can prevent an event as serious as a mechanical collapse in one path from affecting the second path (common cause failure).

***Figure 7** – Redundant architecture for single and dual-corded loads*



The architectures discussed in **Figures 3**, **4**, **5** and **7** incorporate transfer switches. With a larger transfer switch, one failure can bring down an extremely large portion of equipment, whereas failure in a smaller switch will bring down only one rack. For some users, a failure of any one rack has equivalent business consequences as the failure of 50 racks; while for others the isolation of a failure to a single rack is an advantage. For users of the latter type, the Rack ATS provides an added availability advantage of fault isolation.

Another factor to consider is the time needed to repair these switches. A small transfer switch will not be repaired but replaced, and can be kept as a spare part for a very quick swap out. In addition, it can be quickly bypassed if needed. A larger switch will need to be repaired and depending on location, will take a few hours to get a repair person on site. Additional time will be needed to diagnose and repair the system, and if the technician does not have the required part, even more time is lost. Thus, when evaluating some of these more advanced designs, a variety of issues should be evaluated to make an optimal decision. Repair time is considered in the statistical availability model described in the next section.

In general, equipment with only one power cord can be a significant liability when trying to develop a high availability mission critical environment. This is true not only for rack-mounted equipment but also for any mission-critical equipment. Even with the best possible construction, any single point of failure will fail eventually and result in downtime. If a true high availability environment is required, single points of failure in the power distribution must be minimized as much as possible, if not removed completely.

Availability Analysis Approach

An availability analysis is done in order to quantify the impact of having single vs. dual-corded devices. Five availability analyses are performed:

- Case 1 – Single-corded Load from **Figure 2**
- Case 2 – Single-corded Load with Static Transfer Switch from **Figure 3** (single transformer)
- Case 3 – Single-corded Load with Static Transfer Switch from **Figure 4** (redundant transformers)
- Case 4 – Single-corded Load with Rack ATS from **Figure 5**
- Case 5 – Dual-corded Load from **Figure 6**

Linear combinatorial analysis, also referred to as Reliability Block Diagrams (RBD), is used to illustrate the power availability at the outlet for these five configurations. This method of system modeling is the most direct, and works well for systems where there are few state transitions. Linear combinatorial analysis works by using defined reliability data and then developing a system model that represents the configuration being analyzed. Because this analysis focuses only on the differences between the configurations, it is assumed that everything upstream of the UPS system is perfect including utility power. Therefore the availabilities presented here will be higher then what is expected in an actual installation.

The details of the analysis are provided in the Appendix.

Data Used in Analysis

Most of the data used to model the components is from third party sources. Data for the Rack ATS is based on field data for APC's Rack ATS product, which has been on the market for approximately 5 years and has a significant installed base. In this analysis the following key components are included:

1. Terminations
2. Circuit Breakers
3. UPS systems
4. PDU
5. Static Transfer Switch (STS)
6. Rack ATS

The PDU is broken down into three basic subcomponents: Circuit Breakers, Step-down Transformer and Terminations. The subpanel is evaluated based on one main breaker, one branch circuit breaker and terminations all in series. The Rack ATS component is used in the fourth case only. The appendix includes the values and sources of failure rate $\left(\frac{1}{MTTF}\right)$ and recovery rate $\left(\frac{1}{MTTR}\right)$ data for each subcomponent, where MTTF is the Mean Time To Failure and MTTR is Mean Time To Recover.

The failure rates and repair rates used for the analysis are provided in the Appendix.

Assumptions used in the analysis

As with any availability analysis, assumptions must be made to create a valid model. **Table 1** lists the basic assumptions used in this analysis.

***Table 1** – Assumptions of analysis*

Assumption	Description
Failure Rates of Components	All components in the analysis exhibit a constant failure rate. This is the best assumption, given that the equipment will be used only for its designed useful life period. If products were used beyond their useful life, then non-linearity would need to be built into the failure rate.
Repair Teams	For "n" components in series it is assumed that "n" repairpersons are available.
System Components Remain Operating	All components within the system are assumed to remain operating while failed components are repaired.
Independence of Failures	These models assume construction of the described architectures in accordance with Industry Best Practices. These result in a very low likelihood of common cause failures and propagation because of physical and electrical isolation.
Failure Rate of Wiring	Wiring between the components within the architectures has not been included in the calculations because wiring has a failure rate too low to predict with certainty and statistical relevance. Also previous work has shown that such a low failure rate minimally affects the overall availability. Major terminations have still been accounted for.
Human Error	Downtime due to human error has not been accounted for in this analysis. Although this is a significant cause of data center downtime, the focus of these models is to compare power infrastructure architectures, and to identify physical weaknesses within those architectures. In addition, there exists a lack of data relating to how human error affects the availability.
Power Availability is the key measure	This analysis provides information related to power availability. The availability of the business process will typically be lower because the return of power does not immediately result in the return of business availability. The IT systems typically have a restart time which adds unavailability that is not counted in this analysis
No benefit of fault isolation	The failure of any rack is considered a failure, and equivalent to the failure of all racks at once. This assumption understates the advantage of the Cases 4 and 5. For some businesses, the failure of a single rack is of less business consequence than the failure of all racks.

Results

It is important to understand that the objective of this analysis is to compare the theoretical availabilities between cases. Since all components in all five cases share the same failure rate data the only differences between each case are the quantity, MTTR, and placement of the components. This method provides a very effective demonstration of availability effectiveness of one architecture when compared with another.

Availability is measured with respect to the outlet(s) supplying power to the critical load. In every case, the same component reliability data is used. In Case 1, the failure of any one component in that chain would cause the load to drop. This is a baseline case.

In both Cases 2 and 3, any one component from each redundant path would have to fail simultaneously for a dropped load to occur. However the failure of any single component downstream of the STS, including the STS, would also drop the load. The remarkable result in this case is how little the installation of the STS increases system availability. The reason is that the STS is not significantly more reliable than the upstream UPS, and the STS is still a single point of failure. Note further that in case 2 the transformer MTTR minimizes any benefit of the STS.

In Case 4, any one component from each redundant path would have to fail simultaneously for a dropped load to occur. Despite being a single point of failure, the MTTR of the Rack ATS is small due to the fact that it can quickly be replaced if a spare is available. The key finding here is that although the Rack ATS is not necessarily more reliable than the large STS, the much lower MTTR gives it a very large availability advantage.

In Case 5, any one component from each redundant path would have to fail simultaneously for a dropped load to occur. **Table 2** is an overview of the results of the five availability calculations.

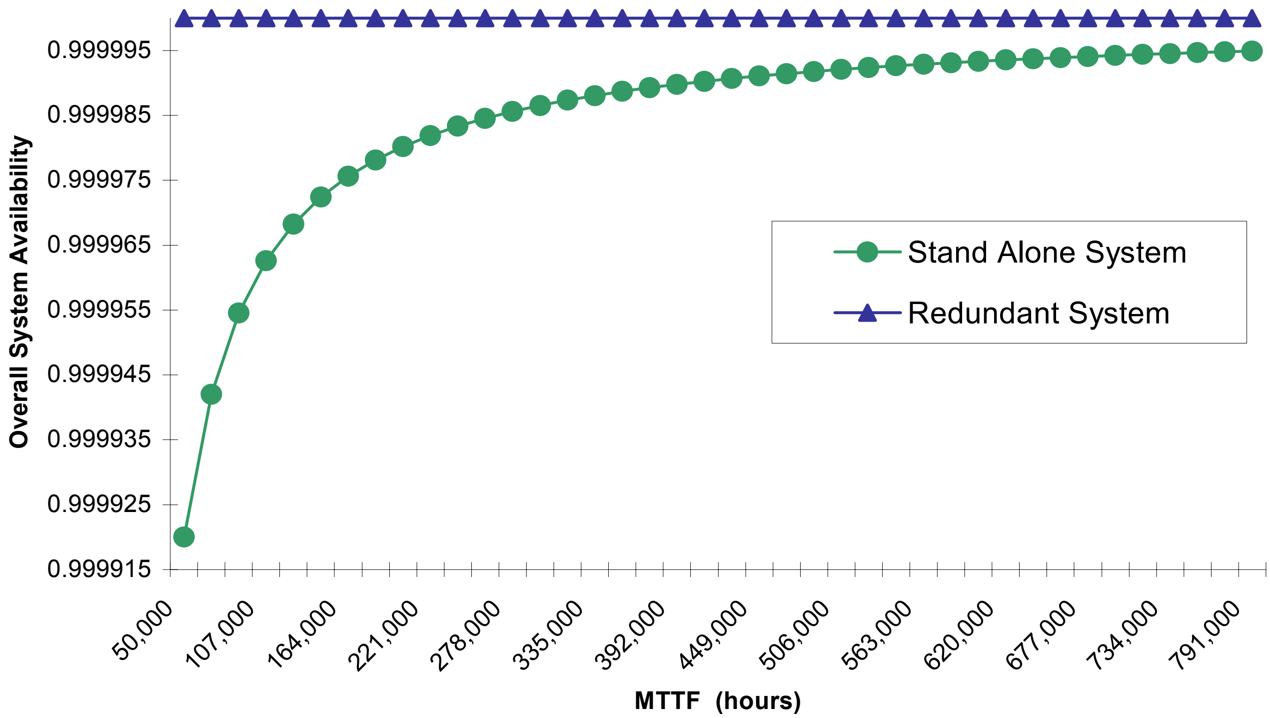
***Table 2** – Summary of availability results*

Case	Configuration	Availability	Number of "9"s
Case 1	Single-corded Load	99.985 %	3.8
Case 2	Single-corded Load with STS (single transformer)	99.98596 %	3.85
Case 3	Single-corded Load with STS (redundant transformers)	99.99715 %	4.5
Case 4	Single-corded Load with Rack ATS	99.999931 %	6.2
Case 5	Dual-corded Load	99.9999977 %	7.6

This analysis illustrates the significance of dual-corded equipment in attaining high availability within a double-ended electrical architecture. The benefits of such an elaborate design are not fully realized with single-corded equipment but come close by implementing a Rack ATS.

From the results presented above it is quite clear that bringing redundancy to the load improves availability. **Figure 8** demonstrates that even if the reliability (MTTF) of a product is increased 10 fold, it still does not provide the same availability as does using a redundant set at a lower reliability level. The redundant system is providing near 100% availability, or a large number of "9's".

***Figure 8** – Availability vs. MTTF*



Conclusions

When implementing a high availability architecture, power distribution to the rack needs to be carefully considered. The typical types of power distribution described in this paper vary by a factor of 10,000 in the magnitude of the downtime they create.

This analysis demonstrates very clearly the importance of using dual-corded equipment in a critical data center. The analysis presented here suggests a full dual path architecture can provide up to 10,000 times less down time than a single path design.

The common practice of using transfer switches to increase the availability of single corded loads provides highly variable results depending on how it is implemented. In some cases, the analysis suggests almost no advantage from the use of a large STS. By contrast, when the transfer switch is moved to the rack the system downtime caused by the power distribution system decreases by a factor of 250.

In addition, the Rack based transfer switch provides additional fault localization since a failure takes out only a single rack. Furthermore, the Rack based transfer switch can be deployed as needed and where needed in a dual path environment.

This data suggests that the common practice of using large STS systems to power single corded loads should be re-evaluated, and that Rack-based transfer switches have significant advantages for approximately similar costs.

In general, the analysis suggests a general principle of bringing redundancy close to the loads to improve availability.

Careful analysis should always be a prerequisite to investing in any high availability system. How much money a customer can justify spending to reinforce their electrical infrastructure determines which solution to select. A customer must have a clear understanding of their business processes so that the cost of downtime can be calculated. This cost is what should ultimately drive any investments in availability.

About the Author:

Victor Avelar is an Availability Engineer for APC. He is responsible for providing availability consulting and analysis for clients' electrical architectures and data center design. Victor received a Bachelor's degree in Mechanical Engineering from Rensselaer Polytechnic Institute in 1995 and is a member of ASHRAE and the American Society for Quality.

Appendix

Components and values

Component	Failure Rate	Recovery Rate	Source of Data	Comments
UPS 675kW / 750kVA	4.0000E-06	0.125	Failure Rate is from Power Quality Magazine, Recovery Rate data is based on assumption of 4 hours for service person to arrive, and 4 hours to repair system	• Used to supply uninterrupted 480 VAC power to the PDU.
Static Transfer Switch (STS)	4.1600E-06	0.1667	Gordon Associates - Raleigh, NC	• Includes controls
Step-down Transformer	7.0776E-07	0.00641	MTBF is from IEEE Gold Book Std 493-1997, Page 40, MTTR is average given by Marcus Transformer Data	• Used to step down the 480 VAC input to 208 VAC outputs, which is required for 120 VAC loads.
Circuit Breaker	3.9954E-07	0.45455	IEEE Gold Book Std 493-1997, Page 40	• Used to isolate components from electrical power for maintenance or fault containment.
6 Terminations	8.6988E-008	0.26316	6 x IEEE value Computed from value by IEEE Gold Book Std 493-1997, Page 41	• Upstream of the transformer, one termination exists per conductor. Since there are 2 sets of terminations between components a total of six terminations are used.
8 Terminations	1.1598E-007	0.26316	8 x IEEE value Computed from value by IEEE Gold Book Std 493-1997, Page 41	• Downstream of the transformer, one termination exists per conductor plus the neutral. Since there are 2 sets of terminations between components a total of eight terminations are used.
Rack ATS	2.0E-06	3	APC Redundant Switch field data	• The APC Rack ATS MTTF is calculated to be 1 million hours. A conservative value of 500,000 hours is used.

Availability of a Single-corded Load [Case 1]

The availability for a single-corded load, from **Figure 2**, is calculated based on the following RBD. **Figure 9** represents the top layer of the RBD, which calculates the steady state availability based on the series components. This RBD incorporates "expandable" blocks for the “Transformer Parts" and the "Subpanel Parts". An expandable block means that there’s a lower level RBD that defines its sub-components. Laying the RBD out in this manner facilitates availability calculations. The Subpanel is used to distribute power directly to the critical equipment. The contents of these blocks are shown in **Figures 10** and **11**.

***Figure 9** – Single-corded load*

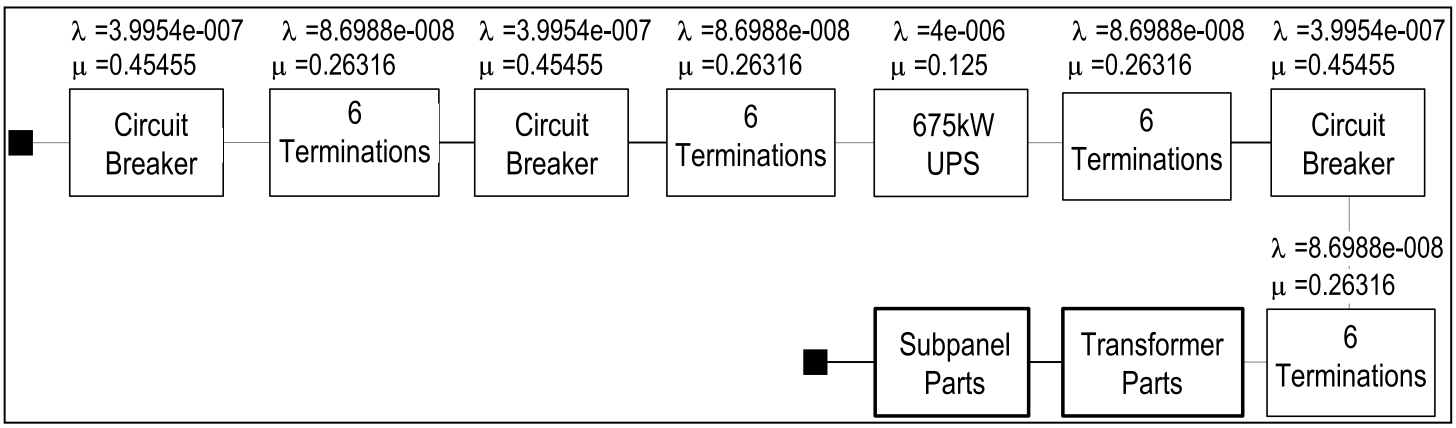


***Figure 10** – Transformer parts*

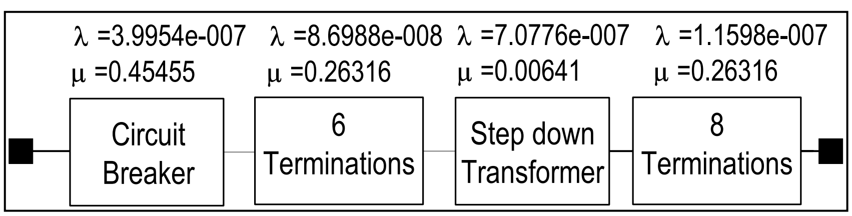
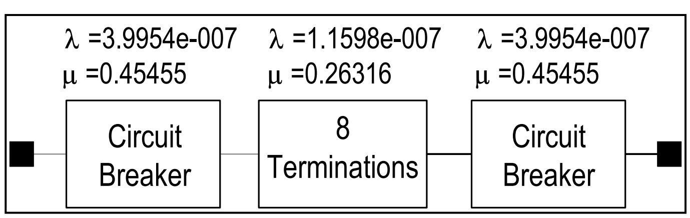


***Figure 11** – Subpanel parts*



Based on the RBD presented above, the availability of the single-corded system is shown below.

Single-corded load availability [Case 1]

Model-Name	Availability	Unavailability	MTTR (hours)	MTTF (hours)	Annual Downtime (hours)
Single-corded Load	**99.98498 %**	**1.5021E-04**	**19.3**	**128,665**	**1.3158**
UPS system	99.99640 %	3.5958E-05	6.5	180291	0.31499
Transformer Parts	99.98879 %	1.1205E-04	85.5	763,201	0.98158
Subpanel Parts	99.99978 %	2.1987E-06	2.4	1,092,825	0.01926

Because the analysis is carried out using data with five significant digits, unavailability is another way to express the results. Unavailability is simply calculated as (1 – Availability).

Availability of a Single-corded Load with Static Transfer Switch (single transformer) [Case 2]

The distribution method from **Figure 3** uses an STS and adds redundancy to everything upstream of it except for the transformer, which is placed downstream. The availability for this scenario is calculated based on 7 RBD strings that are broken out for clarity. **Figure 12** represents the top layer of the RBD. The "UPS system" block is a 1 out of 2 block, meaning that all components within that block are redundant. **Figure 13** shows the contents of the "UPS system" block.

***Figure 12**– Single-corded load with STS*

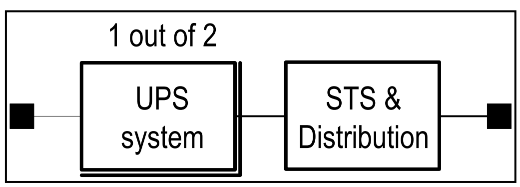
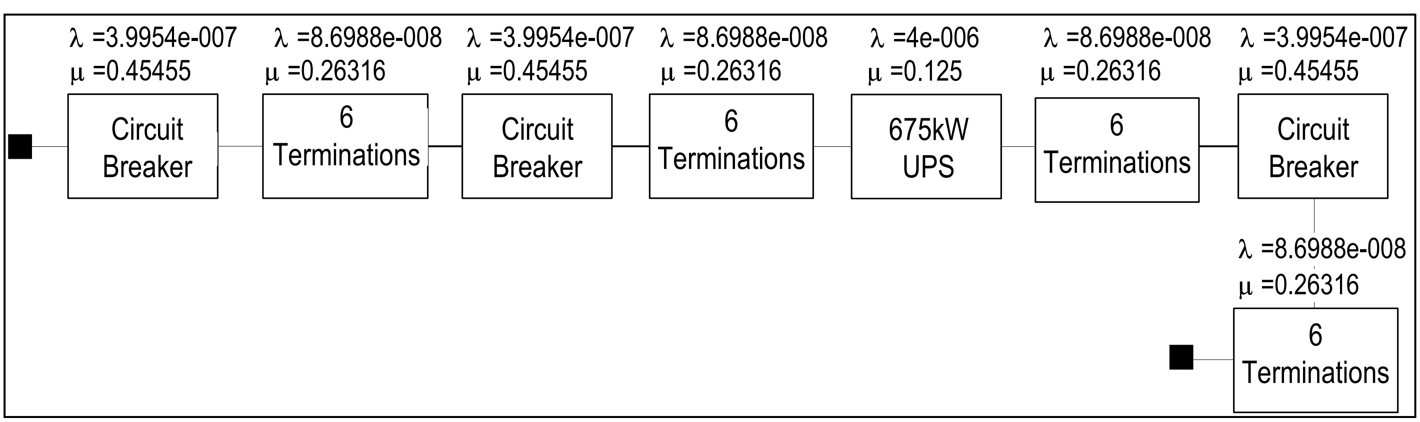


***Figure 13**– UPS system*



Everything upstream of the STS is redundant, however, everything inside the "STS & Distribution" block, shown in **Figure 12** is a single point of failure. The "STS & Distribution" block contains the STS system, transformer parts and the subpanel parts as illustrated in **Figure 14**. The STS system is what allows the use of the upstream redundant components. This system incorporates circuit breakers, terminations and most importantly, the Static Transfer Switch. The RBD for the STS system is shown in **Figure 15**.

Figure 14 *– STS & distribution*

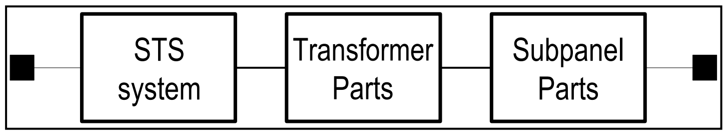
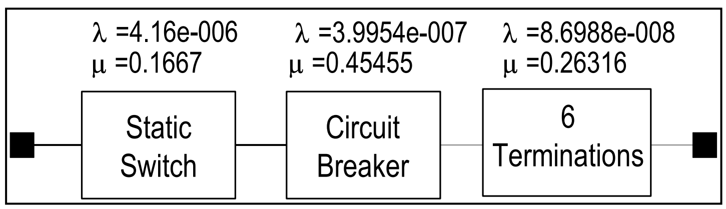


Figure 15 *– STS system*



The contents of the "Transformer Parts" block and "Subpanel Parts" block of **Figure 14** are broken down further in **Figures 16** and **17**

Figure 16 *– Transformer parts*

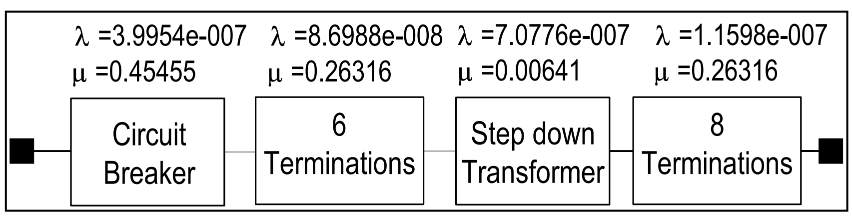
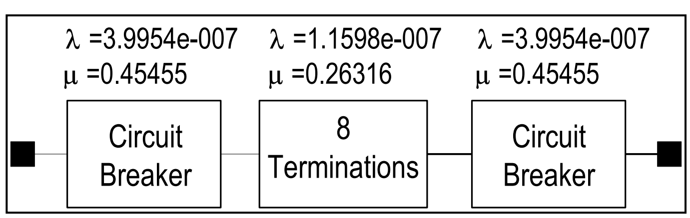


Figure 17 *– Subpanel parts*



Based on the RBD diagrams presented above, the availability of the single-corded system with STS and single transformer is shown in below.

Single-corded load with STS availability (single transformer) [Case 2]

Model-Name	Availability	Unavailability	MTTR (hours)	MTTF (hours)	Annual Downtime (hours)
Singled-corded Load with STS (1 Transformer)	**99.98596%**	**1.4041E-04**	**20.4**	**145,513**	**1.23002**
UPS system	99.99999987%	1.2930E-09	6.5	5,025,125,628	0.00001
Single UPS	99.99640%	3.5958E-05	6.5	180,291	0.31499
STS & Distribution	99.98596%	1.4041E-04	20.4	145,518	1.23001
STS system	99.99738%	2.6164E-05	5.6	215,214	0.22920
Transformer Parts	99.98879%	1.1205E-04	85.53	763,201	0.98158
Subpanel Parts	99.99978%	2.1987E-06	2.4	1,092,825	0.01926

Availability of a Single-corded Load with Static Transfer Switch (redundant transformers) [Case 3]

The distribution method from **Figure 4** uses an STS and adds redundancy to everything upstream of it including the transformer. The availability for this scenario is calculated based on 7 RBD strings similar to the previous analysis. **Figure 18** represents the top layer of the RBD. The "UPS system & Transformer" block is a 1 out of 2 block, meaning that all components within that block are redundant. **Figure 19** shows the contents of the "UPS system & Transformer" block. The “Transformer Parts” block is composed of the same parts as those of **Figure 16**. Up to this point every component has been redundant, however, everything inside the “STS & Distribution” block, shown in **Figure 18**, is a single point of failure.

***Figure 18** – Single-corded load with STS*

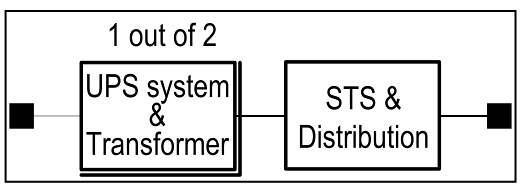
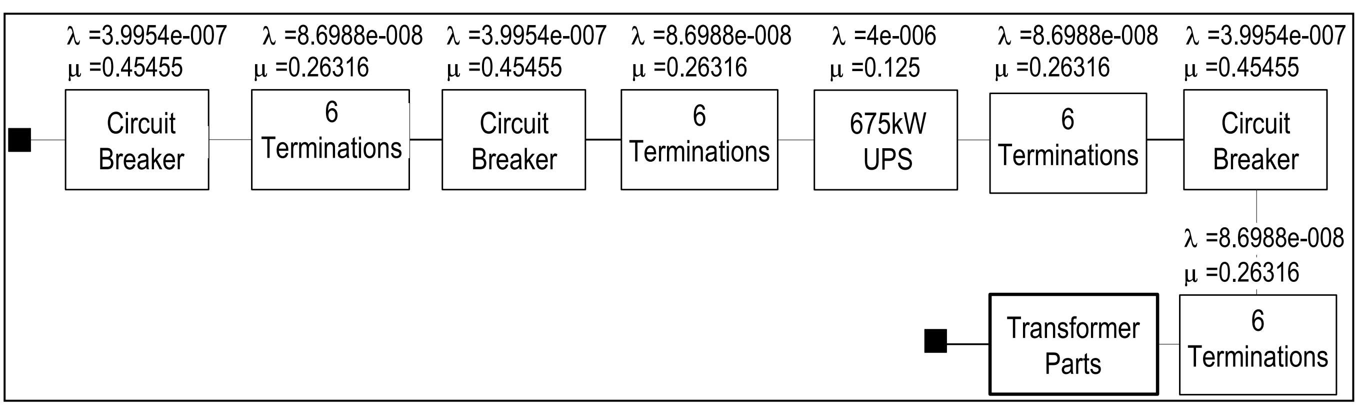


***Figure 19** – UPS system & transformer*



In this case the contents of the "STS & Distribution" block, **Figure 20**, contains only the STS system and the subpanel parts because the transformer is pushed upstream as a redundant component. The "STS system" in this scenario is identical to that of **Figure 16** except that there are 8 terminations rather then 6 as illustrated in **Figure 21**. The components of the "Subpanel Parts" block are identical to those of **Figure 17**.

Figure 20 *– STS & distribution*

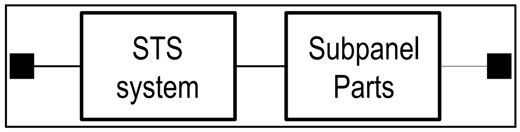
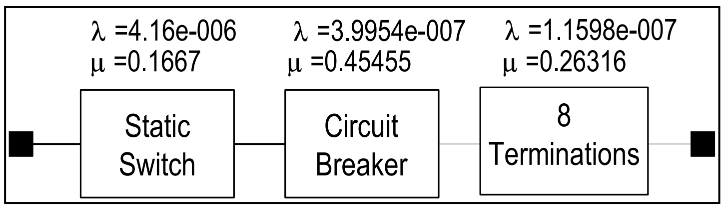


Figure 21 *– STS system*



Based on the RBD diagrams presented above, the availability of the single-corded system with STS and redundant transformers is shown below.

Single-corded load with STS availability (redundant transformers) [Case 3]

Model-Name	Availability	Unavailability	MTTR (hours)	MTTF (hours)	Annual Downtime (hours)
Singled-corded Load with STS (2 Transformers)	**99.99715%**	**2.8495E-05**	**5.1**	**178,839**	**0.24961**
UPS system & Transformer	99.9999978%	2.1906E-08	21.6	985,221,675	0.00019
UPS System	99.99640%	3.5958E-05	6.5	180,291	0.31499
Transformer Parts	99.98879%	1.1205E-04	85.5	763,201	0.98158
STS & Distribution	99.99715%	2.8473E-05	5.1	178,872	0.24942
STSsystem	99.99737%	2.6274E-05	5.6	213,880	0.23016
Subpanel Parts	99.99978%	2.19867E-06	2.4	1,092,825	0.01926

Availability of a Single-corded Load with Rack ATS [Case 4]

The analysis for a single-corded load with a Rack ATS, from **Figure 5**, is calculated based on the RBD in **Figure 22**, which represents the top layer of the RBD. This model now provides redundancy to the rack however the Rack ATS becomes the single point of failure. **Figure 23** shows the components of the "UPS system & Distribution" block. The contents of the "Transformer Parts" and "Subpanel Parts" blocks are identical to those of **Figures 16** and **17** respectively.

***Figure 22** – Single-corded load with Rack ATS*

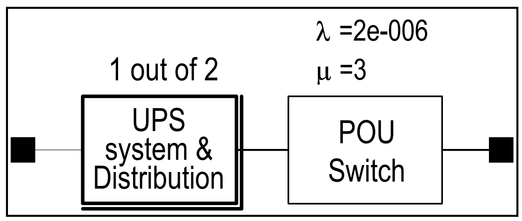
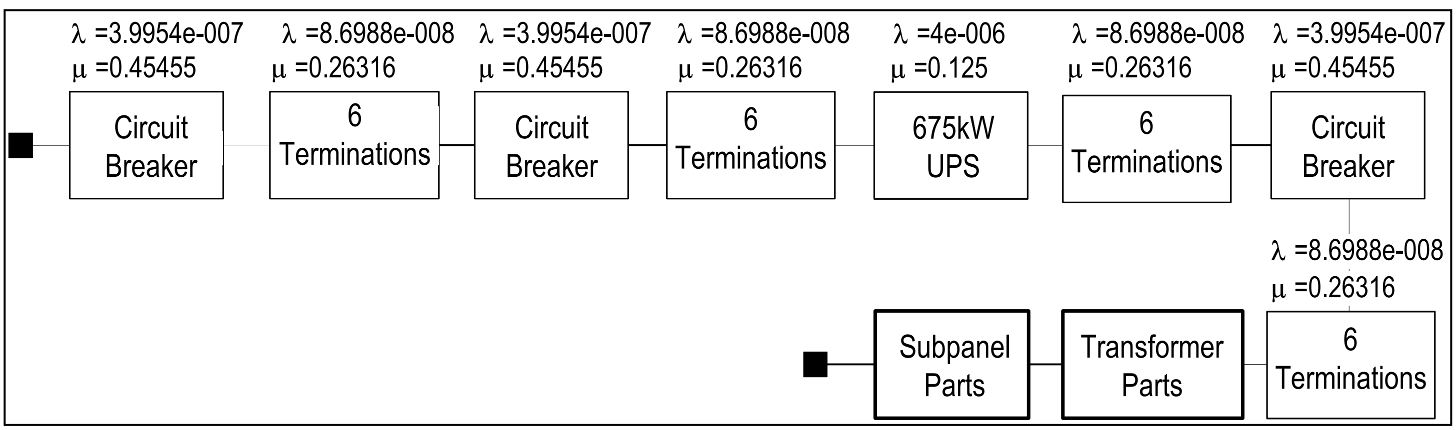


***Figure 23** – UPS system & distribution*



Based on these RBD, the availability of the single-corded system with Rack ATS is shown below.

Single-corded load with Rack ATS availability [Case 4]

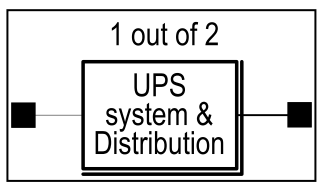
Model-Name	Availability	Unavailability	MTTR (hours)	MTTF (hours)	Annual Downtime (hours)
Single-corded Load with Rack ATS	**99.999931 %**	**3.558950E-07**	**0.4**	**499,705**	**0.00604**
UPS system & Distribution	99.999998 %	2.2562E-08	19.3	856,898,029	0.00018
Transformer Parts	99.98879 %	1.1205E-04	85.5	763,201	0.98158
Subpanel Parts	99.99978 %	2.1987E-06	2.4	1,092,825	0.01926
Rack ATS	99.999933%	3.3333E-07	0.3	500,000	0.00584

In this case, by simply adding another PDU, the availability has drastically improved. However, the Rack ATS is the single point of failure in this system, limiting the overall availability to six "9's". Because of this, a Rack ATS should always be chosen based on its reliability, and spares should always be kept on site to minimize MTTR.

Availability of a Dual-corded Load [Case 5]

The analysis for a dual-corded load, from **Figure 6**, is calculated based on the RBD in **Figure 24**, which again represents the top layer. Like the system with Rack ATS, this RBD calculates the steady state availability based on the overall UPS and PDU failure and recovery rates, however, it does not include the Rack ATS because the load is dual corded and can fully utilize the redundant paths. Only 1 of the 2 paths must be operational to maintain the critical loads. There are no single points of failure in this system. As a matter of fact, even the critical load power supplies are redundant.

***Figure 24** – Dual-corded load*



The lower level RBD that the "UPS system & Distribution" block is composed of are identical to those in **Figures 9 – 11**. Based on these blocks, the availability of the dual-corded system is shown below.

Dual-corded load availability [Case 5]

Model-Name	Availability	Unavailability	MTTR (hours)	MTTF (hours)	Annual Downtime (hours)
Dual-corded Load	**99.9999977 %**	**2.2562E-08**	**19.3**	**856,898,029**	**0.0001976**
UPS system & Distribution	99.9999977 %	2.2562E-08	19.3	856,898,029	0.0001976
Transformer Parts	99.98879 %	1.1205E-04	85.5	763,201	0.98158
Subpanel Parts	99.99978 %	2.1987E-06	2.4	1,092,825	0.01926

In this final case, the "UPS system & Distribution" availability is identical to the previous case yet overall availability has increased to seven "9's". The major difference is that the Rack ATS is no longer needed when using dual-corded equipment. As is shown in the last system, the Rack ATS is a single point of failure and limited the availability to six "9's".