Mitigating Risk of UPS System Failure

Reliability Assessment of CleanSource® HD Integrated Flywheel UPS versus Double-Conversion UPS with Batteries

White Paper 115

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Objective

This paper provides a quantitative analysis of the in-service reliability of Active Power's CleanSource 750HD UPS (uninterruptible power supply) system versus a double-conversion UPS with a single string of batteries. The study quantifies the likelihood of system failure during three different classes of failure – a long utility outage lasting more than 10 seconds, a short utility outage lasting less than 10 seconds, and a demand failure. The study also evaluates the probability of failure of CleanSource 750HD UPS with a secondary energy source (Extended Runtime option) and flywheel energy storage compared to a double-conversion UPS with batteries.

Key Findings

- MTechnology, Inc., found CleanSource 750HD UPS to be more reliable than a double-conversion UPS with a single string of batteries with an 80 percent lower probability of failure in a short utility outage scenario – an outage lasting less than 10 seconds.

- CleanSource 750HD has a lower probability of failure over a one year period than a double-conversion UPS with batteries in a long utility outage. CleanSource 750HD reduces system failure risk by more than 21 percent even with the inclusion of common failure rates of the ATS, main switchgear, and generator in a long utility outage.

- Assuming neither system is in bypass at the moment a utility outage occurs, the likelihood CleanSource 750HD does not support the load is 99 percent lower than the demand failure probability of a double-conversion UPS with batteries.

- During short outages, CleanSource 750HD with Extended Runtime option (modeled as adding the same single string of batteries used in the double-conversion UPS) reduces the probability of failure by 85% versus a double-conversion UPS.

- The automatic transfer switch (ATS) is the most likely cause of a system failure in a long utility outage. ATS failures account for approximately 37 percent and 47 percent of expected system failures of double-conversion UPS with batteries and CleanSource 750HD, respectively.

- The most likely failure mode of a double-conversion UPS with batteries is due to undetected battery failures. Non-detectable and detectable battery failures account for more than 83 percent of all double-conversion UPS failures.

- The study used a conservative (low) non-detectable battery failure rate of 1 percent of all battery failures and assumes effective maintenance and testing. MTechnology's experience strongly suggests that it would be difficult to make a single string of batteries more reliable than the model predicts.

Overview

Active Power, Inc., retained MTechnology, Inc. (MTech) to perform a reliability analysis of its CleanSource 750HD UPS versus double-conversion UPS with batteries. The study built upon a reliability analysis of the Active Power CleanSource UPS performed by MTech in 2007. Refer to Active Power white paper #103 ("Reliability Assessment of Integrated Flywheel UPS versus Double-Conversion UPS with Batteries").

MTech has been applying the science of probabilistic risk assessment (PRA) to the problem of high-availability electric power suitable for computers, Internet industries, and other mission critical facilities since 1996. The firm's clients include manufacturers, engineering firms, owners, and users of mission critical facilities. MTech serves clients across a wide range of industries including corporate data centers, nuclear power, oil and gas, distributed generation, biomedical research, proton beam cancer therapy, and fuel cell development.

The study included two classes of utility failure:

- Long utility outages lasting longer than 10 seconds where the AC source is transferred to generator requiring the automatic transfer switch (ATS) to operate and the generator to start and run.

- Short utility outages lasting less than 10 seconds where the UPS energy storage is sufficient to support the load until utility service is restored and transfer to generator is not considered. This is the most common outage scenario and highlights reliability differences of the two UPS systems.

MTech developed a fault tree model for both systems. The fault tree model combines knowledge of combinations of utility and UPS component failures results in system failure with the frequency of component failures and duration of anticipated repairs.

Data regarding component failures was obtained from published sources such as the IEEE Gold Book, augmented by Active Power's CleanSource UPS fleet experience when possible.

System Descriptions

CleanSource 750HD

The CleanSource 750HD is Active Power's high density flywheel UPS solution rated at 750 kVA / 675 kW. It utilizes a 1,700 lb. flywheel rotating at 7,700 revolutions per minute (RPM) for energy storage. The UPS integrates the functionality of a motor, flywheel rotor, and generator into a single system. (See Figure 1 below)

During normal operation, the flywheel rotates at a constant speed. The system delivers conditioned power from utility to the protected load. When power from the utility is interrupted, the system converts the kinetic energy stored in the flywheel to electrical power. When AC power is restored, the system transfers the load back to the utility or generator.

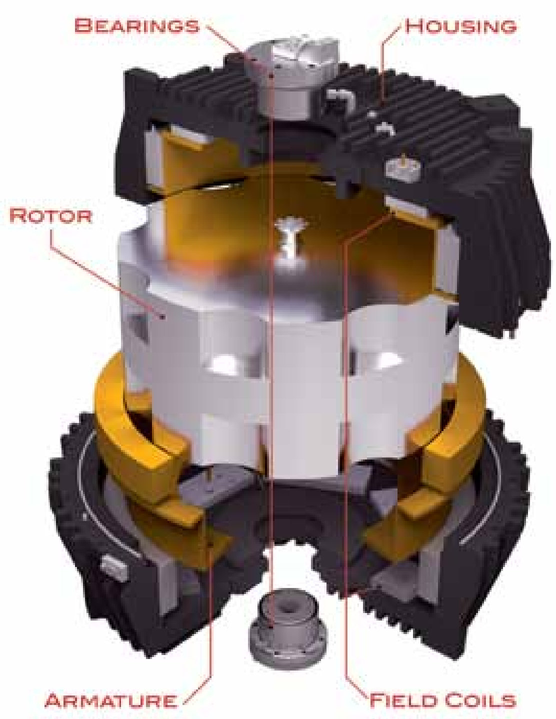


Figure 1: Active Power 750 kVA Flywheel Rotor and Housing

The system provides power conditioning features including voltage regulation and harmonic cancellation. Coupling CleanSource 750HD UPS with a standby generator creates a continuous power system that protects sensitive, mission critical loads from both short power disturbances and extended power outages. The CleanSource UPS fleet has more than 150 million hours of field runtime in applications around the world.

The flywheel rotor is supported by Active Power's magnetic bearing technology. This technology unloads a majority of the flywheel's weight from the field replaceable mechanical bearing cartridge. A vacuum pump evacuates the chamber, reducing the drag on the spinning flywheel. During outages, the flywheel's speed decreases as power is transferred to the load. Regulated current is supplied to the field coils to maintain constant voltage output throughout the discharge.

The system provides power conditioning and ride-through power during voltage sags and surges. It also bridges the gap between a power outage and availability of generator power. The simplified one-line schematic of CleanSource UPS for this analysis is illustrated in Figure 2 below.

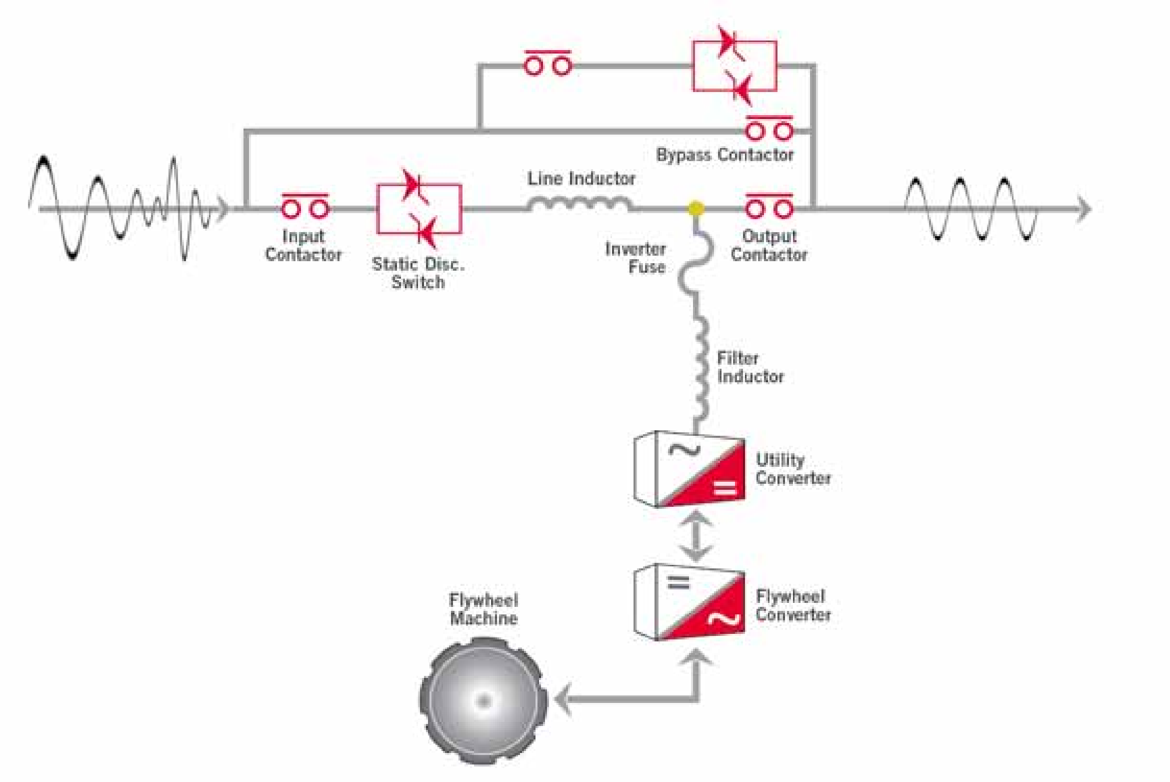


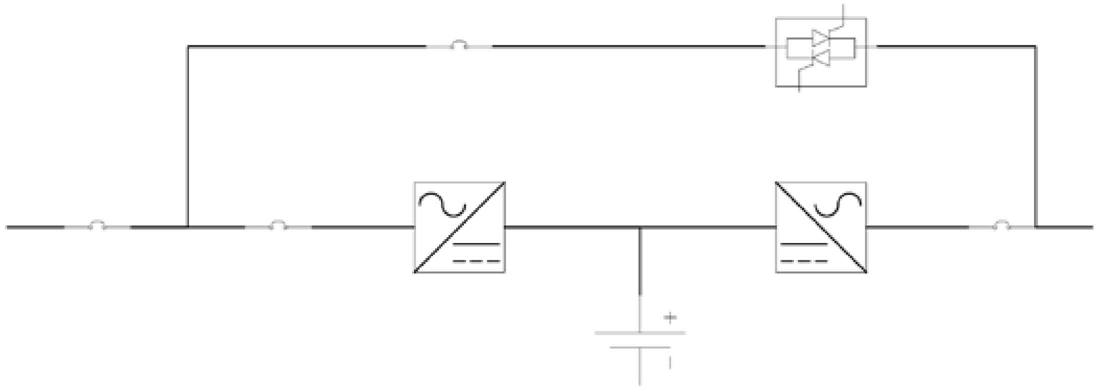
FIGURE 2: ONE-LINE SCHEMATIC OF CLEANSOURCE 750HD UPS

Double-Conversion UPS

The double-conversion UPS is based on a single rectifier-inverter module with a wraparound static bypass switch and a single-string VRLA battery. This is a high-level model with failure modes that include rectifier failure, inverter failure, DC capacitor bank failure, circuit breaker failures, and static bypass failures. A simplified diagram is shown in Figure 3 below.

During an outage at the main input of the UPS, energy is taken from the battery until input power is restored. The rectifier then recharges the battery while simultaneously supplying the inverter with DC power. When the system works as intended, this takes place without interruption of the output of the UPS.

While effective, the drawbacks of a double-conversion system include lower operating efficiencies due to the two-step process of converting utility power from AC to DC, and then from DC to AC. Lead acid batteries are large and heavy and filled with corrosive chemicals and hazardous materials that must be disposed of carefully. Batteries generally require controlled environments. A 10 degrees Celsius increase in ambient temperature reduces the anticipated lifetime by half. Additionally, batteries are susceptible to demand failures that are undetectable during regular maintenance.



Conventional Double Conversion UPS

FIGURE 3: ONE-LINE SCHEMATIC OF DOUBLE-CONVERSION UPS TOPOLOGY

Utility Power, ATS, and Generator System

Both systems have a single incoming utility feed and standby generator connected through switchgear and the ATS to the UPS inputs. The one-line schematics of the utility, generator, ATS, main switchgear, and UPS alternatives are shown below. (Figures 4 and 5)

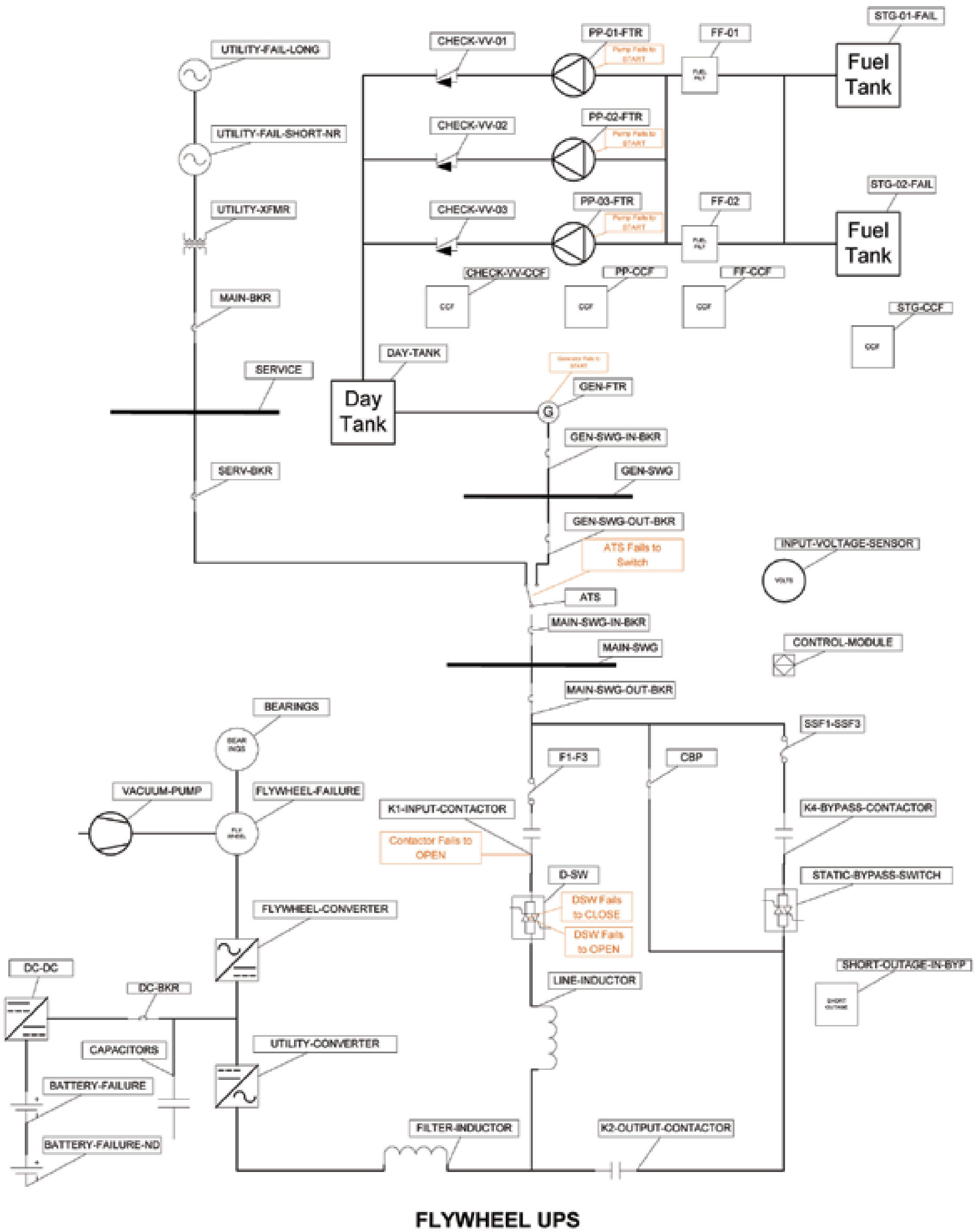
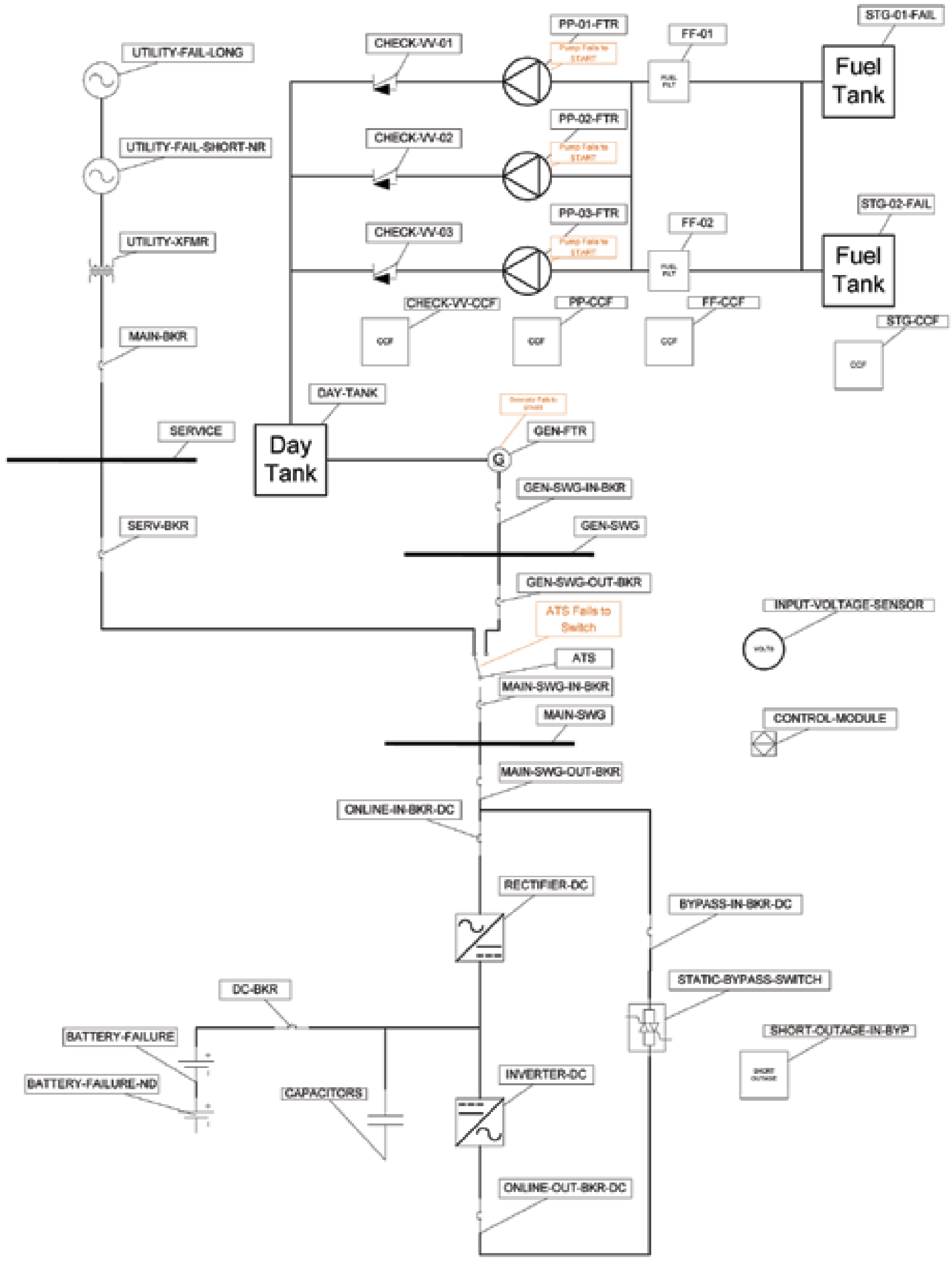


FIGURE 4: CLEANSOURCE 750HD WITH UTILITY AND STANDBY GENERATOR



CONVENTIONAL UPS

Figure 5: Double-Conversion UPS with Utility and Standby Generator

Probabilistic Risk Assesment (PRA)

Introduction

Probabilistic Risk Assessment (PRA) is a collection of formal techniques used to assess the reliability and availability of complex systems. PRA has been extended and refined by military, aerospace, civilian nuclear power, and hazardous process industries. Modern PRA techniques allow for quantitative evaluation of the impact of management decisions and policies, organizational structure, and related environmental factors in addition to physical component failures.

There are two important reasons to use PRA to study highly reliable systems:

- The fundamental limitations of learning about reliability by observing system failures.

- The necessity of quantifying risk for rational and effective allocation of scarce resources.

Claims of “six nines” availability, shorthand for 99.9999 percent average uptime, are rampant in this field. A brief mathematical analysis can show that such claims are equivalent to a mean time to failure (MTTF) of more than 1,200 years. It is impossible to verify or falsify such a claim by observation of a facility with an economic lifetime of a few decades. Neither designer nor owner will live long enough to learn the truth.

PRA techniques allow for the development of credible, defensible estimates of system reliability by combining known data on simpler component failure rates in a formal mathematical model. There is a great deal of component failure rate data available for most electrical, electronic, and mechanical components. PRA calculations allow that data, combined with an expert’s knowledge of how the components in a particular system interact, to produce useful estimates of complex system failure rates before the first system is built.

The ability of PRA to estimate system failure rates allows designers and manufacturers to evaluate the reliability of competing designs before building the first prototype. Predicting the effects of proposed improvements is also a powerful tool. Highly reliable systems invariably utilize redundant components, backup systems, and other techniques. These techniques result in complex designs that defy traditional engineering intuition and judgment.

PRA is necessary to establish the reliability of systems that fail so rarely that direct measurement is impractical. It is also useful when failure is to be avoided to the maximum extent possible as is the case with nuclear plants. The second, and arguably more important, reason to utilize PRA is its implications for management as an aid in decision making.

The results of a good PRA analysis are much richer than a simple number such as mean time to failure (MTTF) or availability. The results are presented both as a probability of failure (discussed below) and as a quantitative ranking of the contribution of each component to the overall risk of failure. It is this quantification of risk that is the most powerful reason to utilize PRA in support of highly reliable systems.

Results for CleanSource 750HD and conventional double-conversion UPS with batteries are consistent both with earlier studies of corporate data centers and with competitors' UPS products. Models with dozens or even thousands of components invariably show that the majority of the risk of failure can be attributed to just a few components. Without this knowledge of the relative contributions to failure, designers and their managers cannot possibly allocate scarce resources most effectively. Armed with the knowledge that only a few components cause most system failures, resources can be allocated to those components. Resources can also be removed from components, maintenance practices, and other efforts that can be shown to make little or no contribution to the reliability of the system.

In summary, PRA provides information regarding the reliability of a system that is difficult or impossible to obtain by other means. That information enables the rational, defensible allocation of resources for enhancing reliability during all phases of design, operations, maintenance, and improvement.

Availability and Probability of Failure

MTech reports results primarily in terms of probability of failure instead of availability. Availability is a metric for repairable systems, but it is not the most useful one for understanding the risks, or the differences between competing systems. The primary reason to use probability of failure is that end-user customers find it the most useful metric. Few firms have substantial experience in the mathematical techniques of PRA, but executives routinely manage risk. Many purchase products such as insurance or disaster recovery programs based upon their assessment of risk, which is the probability of suffering a loss multiplied by the amount of damage they anticipate from such a loss. **Most firms that operate data centers will suffer substantial losses in the event of a single outage and they need to know the probability of that event in order to make informed decisions regarding additional investment or other means of mitigating the risk.**

A final reason to use probability of failure rather than availability is that the probability of failure is a function of time. Analysis methods such as Markov chains and network reduction are limited to constant failure rates and the results are often quoted as MTTF, obtained from a constant failure rate, λ, by inversion:

$$MTTF = 1/\lambda.$$

While this is true for a component or system with constant failure rates, redundant elements with constant failure rates result in a system with variable failure rates. It can be misleading to characterize systems incorporating redundant elements with a constant failure rate.

Fault Tree Modeling

Fault Tree Analysis is a technique used to trace the effects of component or subsystem failure. The analysis starts with system failure. The analyst determines which subsystems must fail in order to cause the system to fail. Each subsystem is similarly evaluated, until all paths end in a number of well-defined failures, called initiating events. Fault tree models are logical models of system failure combined with the failure and repair rates for the initiating events. Combinations of component failures that are sufficient to cause a system failure are known as minimal cut sets. Fault trees and their accompanying analysis tools are the prime modeling technique for determining system minimal cut sets.

Failure and repair rates for each basic event are used to determine the relative contribution of each path to overall system failure. The result of this analysis is a listing of minimal cut sets and their contribution to the overall probability of system failure. Since even simple models typically have thousands of minimal cut sets, but nearly all failures are caused by a few cut sets, MTech does not report the contributions of every cut set.

The CleanSource 750HD and the double-conversion UPS were modeled for comparison using the SAPHIRE fault tree analysis tool. The original model for the CleanSource UPS, developed in 2008, was extended to take into account the design enhancements of the CleanSource 750HD. The original model of the double-conversion UPS was retained for this study.

System failure is defined as failure to get power from the online or the standby path to the critical load. Utility and the standby generator are AC sources. The model compares both UPS systems – Active Power's CleanSource 750HD and the conventional double-conversion UPS/bypass module. Failure occurs if either type of UPS fails. This approach enables the common elements of the fault trees (i.e., utility, generator, etc.) to be shared.

Fault Tree Analysis

MTech utilized component failure rates from many sources including industry publications[1], manufacturers' data, and MTech's experience with the UPS industry. In cases where Active Power provided field data such as experience with the CleanSource fleet, this data was used to inform estimates of the component failure rates and failure modes.

MTech constructed CleanSource 750HD fault trees based upon the one-line schematic diagrams with clarifications from Active Power as required.

Utility Failure Classes

For the purpose of this study, two classes of utility failures were considered.

- Long utility outages lasting longer than 10 seconds where the AC source is transferred to generator requiring the ATS to operate and the generator to start and run.

- Short utility outages lasting less than 10 seconds where the UPS energy storage is sufficient to support the load until utility service is restored and transfer to generator is not considered. This amplifies the core reliability differences of the two UPS systems.

Long Outages: > 10 Seconds with Transfer to Generator

In a long outage scenario, the energy storage in the UPS provides power to the critical load for a short amount of time until the standby generator fires up and assumes the load through transfer of the ATS. It should be noted long outages of greater than 10 seconds are relatively infrequent in developed countries. The Electric Power Research Institute (EPRI) estimates customers are 10 times more likely to experience voltage sags than a complete power outage.

1. IEEE STD-483-1997 (the IEEE Gold Book), now replaced by IEEE Std. 2006.7-2013

Less than 4 percent of complete outages are longer than 10 seconds.

The top cut sets for a double-conversion UPS with batteries and CleanSource 750HD are reproduced in the appendix (Figures A1 and A2). Each of the line items represents a specific failure within the architecture leading to a loss of power to the critical equipment. Each cut set probability is calculated from individual component probabilities or frequency of failures as determined by available industry data, IEEE Gold Book, or field experience from UPS manufacturers.

The fault tree analysis shows ATS failure is the most significant cause of backup power system failure. ATS failures in service participate in about 37 percent of the expected system failures of a double-conversion UPS design and 47 percent of the expected system failures of a flywheel UPS design.

The result is not an indictment of ATS. The IEEE Gold Book data used in the model reports a failure rate of approximately 10^{-5} events per hour or more than 100,000 hours (11+ years) mean time between failures. This represents good performance from a complex electromechanical component in continuous service. The ATS participates in a majority of system failures because it is a single point of failure. The consequence of ATS failures is almost invariably system failure.

Figure 6 shows that the system based on a CleanSource 750HD UPS has a lower probability of failure over one year than systems using double-conversion UPS with batteries. **CleanSource 750HD reduces system failure risk by more than 21 percent even when including the common failure rates of the ATS, main switchgear, and generator.**

	Conventional UPS	CleanSource 750HD
Long Outage P_f	8.58%	6.73%

Figure 6: Summary of System Reliability in Long Utility Outage

Short Outages: < 10 Seconds without Transfer to Generator

In a short outage scenario, the energy storage provides sufficient time to ride-through any power disturbance. Given that 96 percent of all sags and outages are 10 seconds or less, short outage performance is very significant in determining reliability of the individual UPS architectures. The short outage fault tree does not consider failures in ATS, switchgear, and generator. Figures A3 and A4 in the appendix show results of the analysis for the two UPS systems.

Figure 7 shows CleanSource 750HD has a dramatically lower probability of failure than a double-conversion UPS. The probability of a failure (unreliability) is 0.50 percent per year of operation for CleanSource 750HD. **For double-conversion UPS, the probability of failure is 2.46 percent per year, 4.9 times higher than the CleanSource 750HD.**

The fault tree analysis shows that non-detectable and detectable battery failures account for more than 83 percent of all failures in a double-conversion UPS architecture. The assumed failure rate for batteries is based on well-maintained batteries and that the maintenance and testing is effective, resulting in a low battery failure rate. Experience suggests it would be difficult to make the batteries more reliable than the model predicts.

	Conventional UPS	CleanSource 750HD
Long Outage P_f	8.58%	6.73%
Short Outage P_f	2.46%	0.50%

Figure 7: Summary of System Reliability in Short and Long Utility Outage

Demand Failures

Both CleanSource 750HD and double-conversion UPS have demand failure modes. In the case of double-conversion UPS, the demand failure mode is a non-detectable battery failure. This failure is not detectable through monthly system testing and is revealed when the UPS is called upon to support the load during a utility failure. The failure rate for this failure mode is assumed to be 1 percent of the battery base failure rate.

CleanSource 750HD has a demand failure mode that is due to the failure of the disconnect switch and input contactor to open upon the occurrence of a utility failure.

Figure 8 below shows the probability that either of the UPS solutions will suffer a demand failure if the system is not in bypass at the moment the utility outage occurs. **The likelihood CleanSource 750HD will not support the load at the moment of utility outage is very low – less than 1 percent of the demand failure probability of the double-conversion UPS.**

Short Outage	Double Conversion	CleanSource 750HD
Demand Failure Probability	2.05%	$6.7*10^{-5}$%

Figure 8: Demand Failure Probability for Double-Conversion UPS versus CleanSource 750HD

Extended Runtime Option

CleanSource 750HD offers an optional feature allowing users to include an additional battery bank to the flywheel UPS. This combination of two different energy storage technologies improves reliability much more than typical “N+1” or “2N” redundancy based on arrays of identical components. Figure 9 presents a one-line diagram of the CleanSource 750HD with Extended Runtime option.

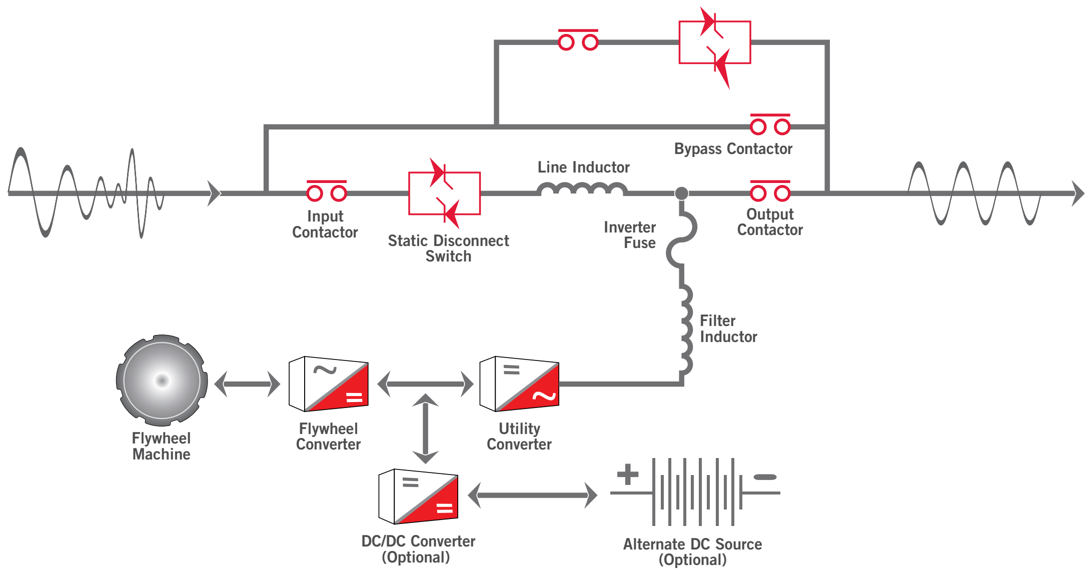


Figure 9: One-Line Diagram of CleanSource 750HD with Extended Runtime

Different technologies provide true "belt and suspenders" redundancy. Failures that disable the flywheel are unlikely to affect the battery and battery failures are unlikely to affect the flywheel system. Redundant arrays of identical components are subject to common cause failures, where a single factor (i.e., manufacturing defect, firmware error, environmental sensitivity, etc.) causes multiple units to fail at the same time.

Common cause failures impose a very strong limit on the benefits of additional redundancy. As shown in Figure 10, the combination of flywheel and battery energy storage technology avoids this limit. MTech's calculations show that adding the same single-string VRLA used in the UPS model to CleanSource 750HD reduces unreliability by approximately 30 percent for short outages. This result is conservative as it does not account for potential increases in battery lifetime caused by the flywheel supplying the energy for all short outages. Short, frequent pulses can reduce battery lifetime, but since the effects are highly dependent on the characteristics of the utility service reliability at a given site, they are not included in this calculation.

	Conventional UPS	CleanSource 750HD	CleanSource 750HD Extended Runtime
Long Outage P_f	8.58%	6.73%	6.60%
Short Outage P_f	2.46%	0.50%	0.36%

Figure 10: Summary of System Reliability in Short and Long Utility Outage with Extended Runtime Option on CleanSource 750HD

Utility Outage Scenarios

As outlined earlier, the study analyzed the reliability of the UPS solutions against long and short outages. For the long outage case, the addition of the battery bank offered in CleanSource 750HD with extended run option decreased the chance of failure to 6.6 percent.

For the more common outages of less than 10 seconds, the study showed CleanSource 750HD with Extended Runtime to have a probability of failure of just 0.36 percent per year of operation – nearly 7 times lower probability than the double-conversion UPS and 28 percent lower CleanSource HD without Extended Runtime.

Demand Failures

As noted above, CleanSource 750HD and double-conversion UPS designs have demand failure modes. The demand failure mode for double-conversion UPS is a non-detectable battery failure, while the demand failure of the CleanSource 750HD stems from a dual failure of the disconnect switch and input contactor to open upon the occurrence of a utility failure.

CleanSource 750HD with Extended Runtime has both of these demand failure modes, but unlike the conventional UPS or CleanSource 750HD it does not fail on a demand if the flywheel system is not operational at the time of an outage unless an undetectable battery failure also occurs. Demand failures of the Extended Runtime version are 30 percent less likely than demand failures in the base version, as shown in Figure 11.

Short Outage	Double Conversion	CleanSource 750HD	CleanSource 750HD Extended Runtime
Demand Failure Probability	2.05%	$6.7*10^{-5}$ %	$4.8*10^{-5}$%

Figure 11: Demand Failure Probability for Double-Conversion UPS, CleanSource 750HD, and CleanSource 750HD with Extended Runtime

Conclusion

MTech's fault tree models considered two different classes of utility failures – long outages lasting more than 10 seconds and short outages lasting less than 10 seconds.

In long outages, the generator must start and run and the transfer switch must operate to successfully support the load. The study found that the probability of system failure is 21 percent lower with CleanSource 750HD UPS than with double-conversion UPS. The difference in UPS reliability is mitigated by the failure probabilities of the generators, ATS, and main switchgear, all of which must operate to support the load.

For short outages less than 10 seconds, CleanSource 750HD is more reliable than a double-conversion UPS, with an 80 percent lower probability of failure. EPRI reports 96 percent of all sags and outages occur within this time period. This scenario is 25 times more frequent than long outages, meaning that facilities are at significantly higher risk from this class of outage. This elevates the importance of the short outage UPS failure rate.

In the double-conversion UPS with batteries, the most likely failure mode is due to undetected battery failures. Detecting battery cells that will fail on the next demand has proven to be extremely difficult. CleanSource 750HD UPS is far more reliable even with optimistic assumptions that monthly tests of the battery string find 99% of battery failures. Realistic estimates of undetectable battery failures results in a clear advantage for the CleanSource 750HD.

The key benefit of a dynamic electromechanical system like that of the CleanSource 750HD is that demand failures are highly unlikely. The normal state of CleanSource UPS is with the flywheel spinning constantly, storing kinetic energy. Changes in values that determine the health of the system are immediate and provide an accurate status prior to an outage occurring. Conversely, a battery-based system is an electrochemical process that, even with monitoring and recommended maintenance, exhibits non-detectable failures. MTech's study showed this, with CleanSource 750HD reducing demand failure probabilities by more than 99 percent compared to double-conversion UPS with batteries.

The new Extended Runtime option of CleanSource 750HD adds another element of reliability to the system. By offering a true "belt and suspenders" approach to energy storage, this feature significantly reduces the risk of common cause failures and offers a significant reduction in the probability of failure in short and long outage scenarios and demand failures.

Appendix - Failure Scenario Cut Sets

FAULT TREE CUT SETS (DETAILED) REPORT					
Project:	CSHD750+BATT		Analysis:	RANDOM	
Fault Tree:	TOP-POWER-FAILURE		Case:	CURRENT	
			Mincut Upper Bound:	8.58E-02	
Cut #	Cut Set %	Prob/Freq	Basic Event	Description	Prob
1	36.6	3.10E-02	ATS	ATS FAILS	3.10E-02
2	28.8	2.50E-02	CONTROL-MODULE	PLC FAILS	2.50E-02
3	23.3	2.00E-02	BATTERY-FAILURE-ND	BATTERY FAILS (NON-DETECTABLE)	2.00E-02
			UTILITY-FAIL-SHORT-NR	UTILITY FAILS	1.00E+00
4	4.1	3.60E-03	GEN-FTR	GENERATOR FAILS TO RUN	4.20E-02
			UTILITY-FAIL-LONG	UTILITY FAILS	8.40E-02
5	1.8	1.60E-03	CAPACITORS	CAPACITORS FAIL	6.60E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
6	1.5	1.30E-03	INVERTER-DC	CONVERTER FAILS	5.30E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
7	1.5	1.30E-03	RECTIFIER-DC	CONVERTER FAILS	5.30E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
8	1.2	1.10E-03	MAIN-SWG-IN-BKR	LARGE CIRCUIT BREAKER FAILS	1.10E-03
9	1.2	1.10E-03	MAIN-SWG-OUT-BKR	LARGE CIRCUIT BREAKER FAILS	1.10E-03
10	1.2	1.00E-03	GEN-FTS	GENERATOR FAILS TO START	1.20E-02
			UTILITY-FAIL-LONG	UTILITY FAILS	8.40E-02
11	1	8.80E-04	MAIN-SWG	BUS FAILS	8.80E-04
12	0.6	4.70E-04	BATTERY-FAILURE-ND	BATTERY FAILS (NON-DETECTABLE)	2.00E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
13	0.1	8.40E-05	ATS-FTS	ATS FAILS TO SWITCH	1.00E-03
			UTILITY-FAIL-LONG	UTILITY FAILS	8.40E-02
14	0.1	8.10E-05	ONLINE-IN-BKR-DC	LARGE CIRCUIT BREAKER FAILS	3.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
15	0.1	8.10E-05	ONLINE-OUT-BKR-DC	LARGE CIRCUIT BREAKER FAILS	3.40E-03

Figure A1: Top Cut Sets for Double-Conversion UPS, Long Utility Outage

FAULT TREE CUT SETS (DETAILED) REPORT					
Project:	CSHD750+BATT		Analysis:	RANDOM	
Fault Tree:	TOP-POWER-FAILURE		Case:	CURRENT	
			Mincut Upper Bound:	6.73E-02	
Cut #	Cut Set %	Prob/Freq	Basic Event	Description	Prob
1	46.6	3.10E-02	ATS	ATS FAILS	3.10E-02
2	36.6	2.50E-02	CONTROL-MODULE	PLC FAILS	2.50E-02
3	5.3	3.60E-03	GEN-FTR	GENERATOR FAILS TO RUN	4.20E-02
			UTILITY-FAIL-LONG	UTILITY FAILS	8.40E-02
4	2.3	1.60E-03	CAPACITORS	CAPACITORS FAIL	6.60E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
5	1.9	1.30E-03	FLYWHEEL-CONVERTER	CONVERTER FAILS	5.30E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
6	1.9	1.30E-03	SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
			UTILITY-CONVERTER	CONVERTER FAILS	5.30E-02
7	1.6	1.10E-03	MAIN-SWG-IN-BKR	LARGE CIRCUIT BREAKER FAILS	1.10E-03
8	1.6	1.10E-03	MAIN-SWG-OUT-BKR	LARGE CIRCUIT BREAKER FAILS	1.10E-03
9	1.5	1.00E-03	GEN-FTS	GENERATOR FAILS TO START	1.20E-02
			UTILITY-FAIL-LONG	UTILITY FAILS	8.40E-02
10	1.3	8.80E-04	MAIN-SWG	BUS FAILS	8.80E-04
11	0.3	2.10E-04	SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
			VACUUM-PUMP	VACUUM PUMP FAILS	8.70E-03
12	0.3	1.70E-04	FILTER-INDUCTOR	INDUCTOR FAILS	7.00E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
13	0.3	1.70E-04	LINE-INDUCTOR	INDUCTOR FAILS	7.00E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
14	0.2	1.00E-04	K1-INPUT-CONTACTOR	CONTACTOR FAILS	4.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02

Figure A2: Top Cut Sets for CleanSource 750HD, Long Utility Outage

FAULT TREE CUT SETS (DETAILED) REPORT					
Project:	CSHD750+BATT		Analysis:	RANDOM	
Fault Tree:	SHORT-OUTAGE		Case:	CURRENT	
			Mincut Upper Bound:	2.46E-02	
Cut #	Cut Set %	Prob/Freq	Basic Event	Description	Prob
1	80.9	2.00E-02	BATTERY-FAILURE-ND	BATTERY FAILS (NON-DETECTABLE)	2.00E-02
			UTILITY-FAIL-SHORT-NR	UTILITY FAILS	1.00E+00
2	6.3	1.60E-03	CAPACITORS	CAPACITORS FAIL	6.60E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
3	5.1	1.30E-03	INVERTER-DC	CONVERTER FAILS	5.30E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
4	5.1	1.30E-03	RECTIFIER-DC	CONVERTER FAILS	5.30E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
5	1.9	4.70E-04	BATTERY-FAILURE-ND	BATTERY FAILS (NON-DETECTABLE)	2.00E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
6	0.3	8.10E-05	ONLINE-IN-BKR-DC	LARGE CIRCUIT BREAKER FAILS	3.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
7	0.3	8.10E-05	ONLINE-OUT-BKR-DC	LARGE CIRCUIT BREAKER FAILS	3.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
8	0.2	5.80E-05	BATTERY-FAILURE	BATTERY FAILS	2.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
9	0.1	2.50E-05	DC-BKR	LARGE CIRCUIT BREAKER FAILS	1.10E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02

Figure A3: Top Cut Sets for Double-Conversion UPS, Short Utility Outage

FAULT TREE CUT SETS (DETAILED) REPORT					
Project:	CSHD750+BATT		Analysis:	RANDOM	
Fault Tree:	SHORT-OUTAGE		Case:	CURRENT	
			Mincut Upper Bound:	4.97E-03	
Cut #	Cut Set %	Prob/Freq	Basic Event	Description	Prob
1	31.4	1.60E-03	CAPACITORS	CAPACITORS FAIL	6.60E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
2	25.4	1.30E-03	FLYWHEEL-CONVERTER	CONVERTER FAILS	5.30E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
3	25.4	1.30E-03	SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
			UTILITY-CONVERTER	CONVERTER FAILS	5.30E-02
4	4.2	2.10E-04	SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
			VACUUM-PUMP	VACUUM PUMP FAILS	8.70E-03
5	3.3	1.70E-04	FILTER-INDUCTOR	INDUCTOR FAILS	7.00E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
6	3.3	1.70E-04	LINE-INDUCTOR	INDUCTOR FAILS	7.00E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
7	2.1	1.00E-04	K1-INPUT-CONTACTOR	CONTACTOR FAILS	4.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
8	2.1	1.00E-04	K2-OUTPUT-CONTACTOR	CONTACTOR FAILS	4.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
9	2	9.80E-05	F1-F3	FUSE FAILURE	4.10E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
10	0.4	2.10E-05	BEARINGS	BEARINGS FAIL	8.80E-04
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
11	0.4	2.10E-05	FLYWHEEL-FAILURE	FLYWHEEL FAILS	8.80E-04

Figure A4: Top Cut Sets for CleanSource 750HD, Short Utility Outage

FAULT TREE CUT SETS (DETAILED) REPORT					
Project:	CSHD750+BATT		Analysis:	RANDOM	
Fault Tree:	TOP-POWER-FAILURE		Case:	CURRENT	
			Mincut Upper Bound:	6.60E-02	
Cut #	Cut Set %	Prob/Freq	Basic Event	Description	Prob
1	47.5	3.10E-02	ATS	ATS FAILS	3.10E-02
2	37.4	2.50E-02	CONTROL-MODULE	PLC FAILS	2.50E-02
3	5.4	3.60E-03	GEN-FTR	GENERATOR FAILS TO RUN	4.20E-02
			UTILITY-FAIL-LONG	UTILITY FAILS	8.40E-02
4	2.4	1.60E-03	CAPACITORS	CAPACITORS FAIL	6.60E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
5	1.9	1.30E-03	SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
			UTILITY-CONVERTER	CONVERTER FAILS	5.30E-02
6	1.6	1.10E-03	MAIN-SWG-IN-BKR	LARGE CIRCUIT BREAKER FAILS	1.10E-03
7	1.6	1.10E-03	MAIN-SWG-OUT-BKR	LARGE CIRCUIT BREAKER FAILS	1.10E-03
8	1.5	1.00E-03	GEN-FTS	GENERATOR FAILS TO START	1.20E-02
			UTILITY-FAIL-LONG	UTILITY FAILS	8.40E-02
9	1.3	8.80E-04	MAIN-SWG	BUS FAILS	8.80E-04
10	0.3	1.70E-04	FILTER-INDUCTOR	INDUCTOR FAILS	7.00E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
11	0.3	1.70E-04	LINE-INDUCTOR	INDUCTOR FAILS	7.00E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
12	0.2	1.00E-04	K1-INPUT-CONTACTOR	CONTACTOR FAILS	4.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
13	0.2	1.00E-04	K2-OUTPUT-CONTACTOR	CONTACTOR FAILS	4.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
14	0.2	9.80E-05	F1-F3	FUSE FAILURE	4.10E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
15	0.1	8.40E-05	ATS-FTS	ATS FAILS TO SWITCH	1.00E-03
			UTILITY-FAIL-LONG	UTILITY FAILS	8.40E-02

Figure A5: Top Cut Sets for CleanSource 750HD with Extended Runtime, Long Utility Outage

FAULT TREE CUT SETS (DETAILED) REPORT					
Project:	CSHD750+BATT		Analysis:	RANDOM	
Fault Tree:	SHORT-OUTAGE		Case:	CURRENT	
			Mincut Upper Bound:	3.58E-03	
Cut #	Cut Set %	Prob/Freq	Basic Event	Description	Prob
1	43.6	1.60E-03	CAPACITORS	CAPACITORS FAIL	6.60E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
2	35.3	1.30E-03	SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
			UTILITY-CONVERTER	CONVERTER FAILS	5.30E-02
3	4.6	1.70E-04	FILTER-INDUCTOR	INDUCTOR FAILS	7.00E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
4	4.6	1.70E-04	LINE-INDUCTOR	INDUCTOR FAILS	7.00E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
5	2.9	1.00E-04	K1-INPUT-CONTACTOR	CONTACTOR FAILS	4.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
6	2.9	1.00E-04	K2-OUTPUT-CONTACTOR	CONTACTOR FAILS	4.40E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
7	2.7	9.80E-05	F1-F3	FUSE FAILURE	4.10E-03
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
8	1.9	6.70E-05	DC-DC	DC-DC CONVERTER FAILS	5.30E-02
			FLYWHEEL-CONVERTER	CONVERTER FAILS	5.30E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02
9	0.7	2.50E-05	BATTERY-FAILURE-ND	BATTERY FAILS (NON-DETECTABLE)	2.00E-02
			FLYWHEEL-CONVERTER	CONVERTER FAILS	5.30E-02
			SHORT-OUTAGE-IN-BYP	SHORT (< 10 SEC) UTILITY OUTAGE WHILE IN BYPASS	2.40E-02

Figure A6: Top Cut Sets for CleanSource 750HD with Extended Runtime, Short Utility Outage