XMBS: A New UPS Bypass Architecture

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Abstract - UPS systems are designed to provide clean AC power for critical loads. In normal operation the utility input is "double converted" and supplied to the load, harmonic and transient free. There are also redundant systems in case of utility failure: a battery source can supply energy temporarily, and a backup generator can support long term outages. Combined, these ensure a reliable energy source. To achieve very high availability the inverter itself also requires redundancy, usually accomplished through paralleling systems or modules, depending on whether it is a monolithic or modular system. And finally, some systems have static bypass circuits which can directly connect the utility to the load in case of inverter failure.

Despite these efforts, there are still single points of failure that can cause the load to be dropped. For example: power surges (lightning strikes) can cause widespread damage, inverter control systems can malfunction, inter-module communication can fail, or safety and protection mechanism can experience nuisance trips. But most failures occur when transferring between power sources, especially operator error during maintenance operations.

When engineers at Alpha Technologies (an EnerSys company) analyzed the reliability and availability of a typical AMPs UPS installation, the opportunity for the biggest improvement was determined to be the maintenance bypass component. The ideal system includes an internal bypass switch for synchronized source transfer, an external static bypass switch in case of inverter failure, and an external bypass switch to isolate the inverter system for maintenance.

This architecture has several problems. Firstly, the cost is prohibitive so that most systems omit the static bypass, and many (especially smaller) systems exclude the external bypass switch. Secondly, the operation of the internal and external switches depends on a sequence of manual operations. Even with significant training this can still be challenging, because it is infrequently practiced, and must be done urgently when the load power is interrupted. Finally, it turns out in practice that the Inverter and Static Transfer Switches are not truly independent, and sometimes a failure in one can cause a failure in the other. To address these issues a new bypass architecture XMBS was developed, to be trialed in the market staring in Q2 of 2019.

This presentation will include:

1. A practical review of the reliability of UPS.
2. A discussion of the challenges of providing reliable power in a manner that meets safety and regulatory requirements (EPO, back-feed, breaker configurations).
3. The design of the XMBS including the technical factors, design decisions, and testing, that was part of the development of the XMBS.
4. A summary of the current status, as well as expectations, for how the XMBS fits into the UPS ecosystem.

I. INTRODUCTION

Reliable AC power is critical for many telecom, cable and datacenter systems. Suppliers have responded with a wide range of UPS equipment that can be configured and optimized for each application. While most equipment has continuously evolved, a critical component – the maintenance bypass – remains unchanged even though it is a single point of failure and, in practice, a significant factor in system reliability.

This document starts with an explanation of maintenance bypass, how it fits into the general system and, in particular, impacts reliability. A description of a new patent pending technology, the "Smart Bypass" will then be introduced, including a summary of the features and benefits along with a description of the implementation and testing to validate the claims. We will then return to the system level and compare how the Smart Bypass compares with alternate products, and finally propose some potential future applications of the same technology to create the ideal reliable system.

A technical note for those experienced in Reliability Analysis. It is a challenge to collect accurate reliability data, because it isn't collected or because it is proprietary. Also, the variety of possible architectures, each with complex causal interactions between components, compounds the challenge. Therefore, for both clarity and practicality in this document, the author uses simplified designs which, while they omit components, are still believed to accurately reflect the relative impact of those being discussed.

For those not familiar with Reliability Analysis, I provide a brief caveat about MTBF at the end of the document.

II. BACKGROUND

A typical UPS system with traditional Maintenance Bypass is shown in Figure 1. The key functions of the Maintenance Bypass are (1) making a connection between the AC source to the load and (2) isolating the UPS output from AC so that it can be safely repaired or replaced. Additionally, to maintain continuous power to the load, the switch must make the AC source connection first, momentarily allow the UPS, Utility, and Load to be connected all together, and subsequently disconnect the UPS output. In industry language, a make before break (MBB) transition is required to avoid "dropping the load".

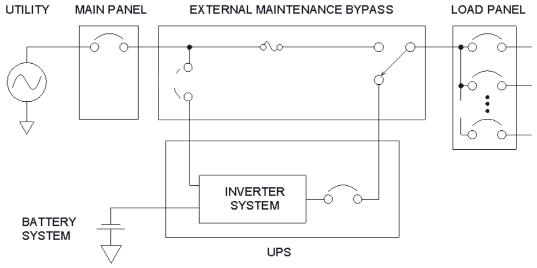


Figure 1: Critical Power System with Maintenance Bypass

The two common architectures of Maintenance Bypass - Rotary switch and Breaker-Breaker - are shown below in Figure 2 and Figure 3 respectively.

A Rotary Bypass consists of a rotor with cross connections and wipers for each electrical connection. As the rotor moves the appropriate connection sequence is made. An internal spring mechanism prevents the switch from staying in an intermediate position, making the operation both simple and predictable. However, reasonable cost rotary switches are only available at lower current levels ($\leq$ 250A) and they don't have a high short-circuit current rating. Therefore, fuses or breakers are usually placed in series with each connection to act as protection devices.

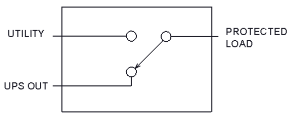


Figure 2: Rotary Maintenance Bypass

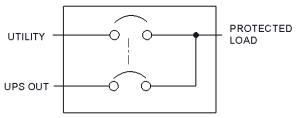


Figure 3: Breaker-Breaker Maintenance Bypass

Breaker-Breaker Maintenance Bypass design eliminates the need for separate protection simply by using breakers as the switches themselves; however properly sequencing the breaker operation becomes a challenge. The standard solution is to use mechanical breaker locks (referred to as Kirk Key Interlocks after the major manufacturer), where the sequence is controlled by capture and release of keys. While allowing higher currents by using larger breakers, the disadvantage is the operation complexity requires more training and can still be confusing for operators, especially when under the stress of trying to recover a load.

Neither the Rotary Switch nor Breaker-Breaker bypass is actually suitable for arbitrarily switching the load because connecting the inverter output to the AC source directly could create large transient currents and trip the protection devices. Instead the Inverter output is first switched to the AC source internally, either using a static bypass switch or another internal bypass.

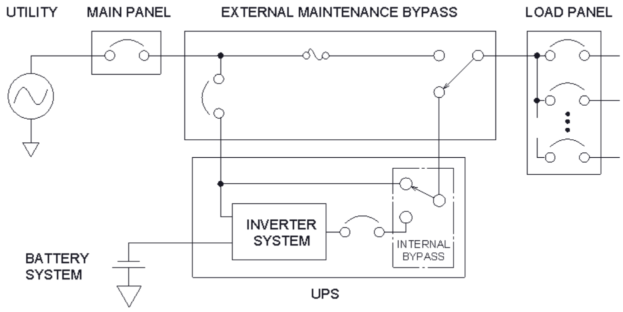


Figure 4: UPS System exposing Internal Bypass

If you think having an both internal and external bypass is unnecessary and reduces reliability, I would agree; however historically it has been needed. With an internal bypass the manufacturer of the UPS takes responsibility for the AC source-to-inverter transition, which includes protecting the load and inverter from any transients that might cause service interruption or damage. Then the external bypass must only switch between two sources which are in fact the same, and of course it must be external to provide the necessary isolation.

III. COMMON CAUSE EFFECTS

Significant efforts and advancements in UPS technology have led to systems with high Availability reliability, and theoretical analyses usually report >1M hours MTBF (114 years). Anecdotal information indicates a much lower practical result. The reason seems to be the under-estimated impact of problems which simultaneously effect multiple, supposedly independent, components. In reliability analysis these are categorized as "common cause" problems and they include catastrophic failures, cascading failures, design flaws, and most of all, human error. The Uptime Institute, a respected consulting firm focused on Datacenter Reliability has reported on this regularly. In a *2016 Survey of Site Downtime* they reported that 79% of electrical system failures were from UPS to load, and 49% of these were caused by humans. In their *2018 Data Center Survey Results* they reported 11% of surveyed datacenters had experience a power failure outage. In their 2019 Webinar, "Data Center Outage Trends, Causes and Costs," they listed the 7 main causes: :

1. Lightning strikes, leading to surges ad lost power. Back-up software/configuration failed.
2. Intermittent failures with transfer switches, leading to failure or transfer to second data center
3. UPS failures and failure to transfer to secondary system
4. Operator errors, turning off/misconfiguring power
5. Utility power loss and subsequent of failure of generator or UPS
6. Damage to IT equipment caused by power surges
7. IT equipment not equipped with dual power supplies to secondary feed

Note that four of the leading causes were related to power transfer between and configuration of between sources, two were related to light strikes and power surges, and only one was a lack of designed in backup.

As a leading supplier of UPS systems to the cable TV market, we already understood the necessity for thorough operator training for using Maintenance Bypass switches, due to both the complexity of operation and the stressful conditions that operators can be under. After doing a Reliability Analysis of the current systems, the opportunity to significantly increase reliability led to a development program and eventually the “Smart Bypass”.

IV. DESIGN SPECIFICATION

The initial criteria set for the “Smart Bypass” design are all focused on reliability:

Criterion	**Reason**
Condition Checking	The bypass must verify conditions are suitable before switching and never drop a load.
Ease of Use	Operation should be obvious without (or at least with minimal) training.
Breaker Based	Fewer components in Breaker-Breaker bypass architectures make them inherently more reliable, and they are suitable for all power levels.
Bi-stable Actuation	A bypass transfer must predictably complete once started so the required energy must be stored in advance and must not be affected by operator interaction.
Reliability	The bypass must be as reliable as existing options, and due to the conservative nature of the market, demonstratable.
Cost	The cost must be similar (within 20%) of existing bypass options due to cost sensitivity of market.

To meet these requirements a unique design was created, the “Smart Bypass” as shown in Figure 5. At the core of design is one breaker mounted right-side up beside another mounted upside down. Doing so means when both handles are pushed in one direction one of the breakers turns on, while the other turns off. This allows a single actuator to perform the switching sequence with a single motion.

Importantly, the actuating mechanism is a single separate assembly. Thus, when it is not operating, the reliability is equal to the breakers themselves, and should any problem arise, the entire assembly can be quickly replaced.

In order to implement the Make-before-Break sequence the actuator needed a unique design. Rather than tightly coupling to the breaker handles, the actuator has openings within which the handles are free to move. The geometry is such that when the actuator moves, the edge of one window first contacts and moves one breaker to the “on” position and only then does the second window contact the second breaker and turn it off. The design of the openings and the speed of the actuator must take into account geometry of the breaker handle motion, acceptable forces on the breakers, motion from the bi-stable mechanisms of the breakers themselves. A tolerance stack-up analysis as well as modelling and thorough testing confirmed there is enough margin (approximately 5mm) for a very reliable system.

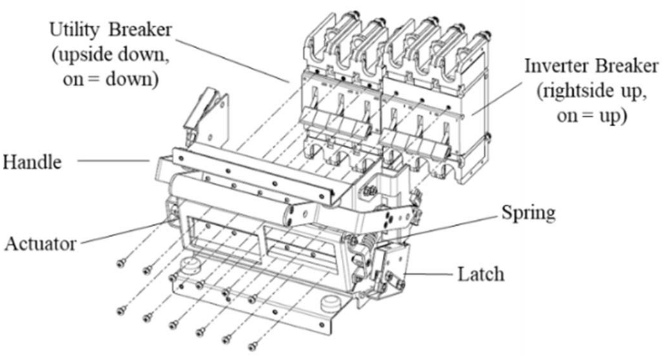


Figure 5: Transfer Mechanism Modular Assembly

To achieve the desired simple actuation and reliable bi-stable motion, two simple rotating linkages with an interconnected spring are used. One link is the operator handle which extending through the case provides an obvious indication of the desired state. The other link is the actuator which rotates about the same axis at the breaker handles. Because the spring is between the two links, it stably holds the switch in position until the handle is moved beyond the center line of the actuator, and then the handle and actuator are driven in opposite directions to complete the motion.

If all that were desired were to simplify the actuation of a breaker-breaker bypass the design would be complete at this stage; however, preventing mis-operation requires a way to prevent motion. Locking the handle position was considered but not chosen for two reasons. Firstly, the operator may try to force the handle and damage the switch. Secondly if conditions were not suitable, the operator would continuously have to try moving the handle until they were. Therefore, the internal actuator was fitted with a latch instead. With this design the operator could move the handle to the desired state, and when conditions were suitable, the switch would transfer.

To meet the reliability requirement, one final feature was added. Because the control system represented a source of error, an over-ride feature was needed. A sliding lever was added to each latch with access through a small hole in the front cover. Although it circumvents the protections provided by the design, this eliminates any possible single point of failure.

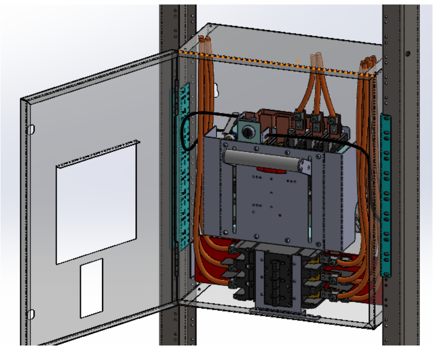
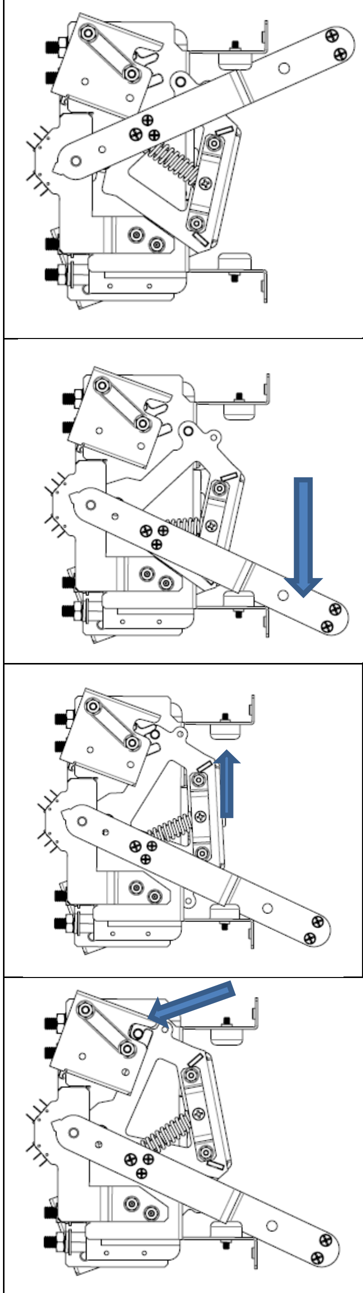


Figure 6: 100A Smart Bypass designed into 19" Rack

V. OPERATION & CONTROLLER

After designing the mechanical system to be equally reliable to a breaker-breaker bypass, the overall reliability and availability are increased though a fault-tolerant control system. Some of the key features are:

1. Mechanical over-ride features for operation without power or in the unlikely event the controller fails.
2. Redundant controller power supplies sourced separately from the Inverter source, Utility Source and a 48Vdc auxiliary supply.
3. Load Protection hardware which prevents transfer if any phase would experience a loss of power. This circuit is made fail safe by only providing power to the latch release under the right conditions and over-rides all other checks.
4. Phase Comparator circuit which compares the desired and selected sources and prevents transfer unless they are within 1 degree. (Industry standard is <15Vac difference which corresponds to 7 degrees for 120Vac. 1 degree achieves ~2 Vac difference and provides margin for changing phase). Phase synchronization is initiated by a request signal from the bypass, manually by the operator at the UPS interface, or by opening the UPS input circuit breaker so that it free runs (known as an "opportunistic" transfer). In all cases the bypass tracks both the phase difference and the stability of the phase difference to make sure transfer will complete in ideal conditions.
5. The Phase Synchronization check ensures that the phase between the voltages of the corresponding phases of the AC sources are within an acceptable angle. Industry standard is that voltage difference should upon transfer should be less than 15Vac, corresponding to approximately 7 degrees for 120Vac system. The controller monitors the zero crossing of corresponding phases from the Connected and Desired source, and prevents transfer if they are above a set threshold, for example 1 degree. In the preferred embodiment, this check is implemented in hardware circuitry so that regardless of microprocessor state the synchronization check will function.
6. Auto-transfer circuit detects power failure of the Inverter and releases the switch to Utility mode. (Restores power to load after brief interruption similar to transfer switch). It includes a recovery feature for when AC power is lost and the Inverter batteries are depleted. In this case, the auto-transfer will hold off upon return of AC power to allow Inverter time to initialize.
7. Checks the phase of the Utility and Inverter wiring to make sure it is done properly. (L2 Utility not wired to L3 Inverter, for example)
8. CAN bus-connected microprocessor controller which monitors voltages and currents of each port to provide near-revenue grade power metering capability through touchscreen graphical interface.
9. Remote activation of switch though controller. This would be used if redundancy of the inverter were compromised if the alternate sources were deemed more reliable until technicians could be dispatched for repairs.
10. Self-diagnostic/Predictive Maintenance. Every operating cycle of the bypass is recorded in real time and performance is compared to previous cycles. It has been determined that wear-out failures can be readily identified with changes in timing. In addition, the breaker position auxiliary contacts are wired to generate an alarm should breakers ever both be in the same position (on or off).



Starting Position with switch in "Bypass" mode

Handle is up and actuator is down with spring holding them stably in these positions. When the actuator is down the Utility breaker is on and the Inverter breaker is off.

Handle moved down to request Inverter Mode

The geometry of the handle and spring now push the actuator up, however the latch on the opposite side (not visible in this view) prevents motion.

Transfer to Inverter Mode

The controller released the latch and the actuator is travelling upward. Motion is deterministic and controls the make-before-break sequence to ensure a brief but guaranteed overlap.

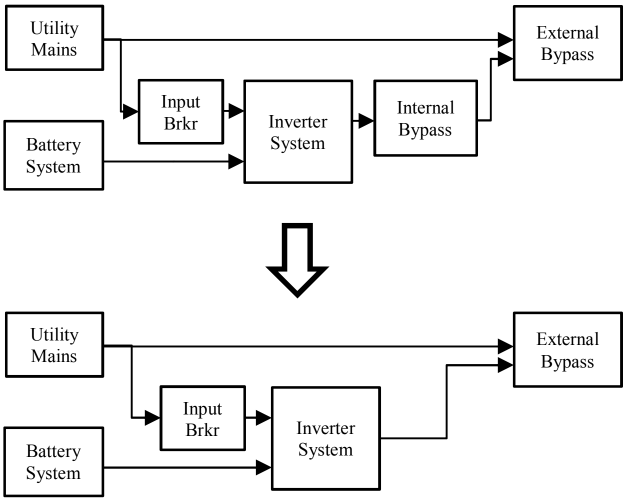
Final postiion with switch in "Inverter Mode"

The swtich in the Bypass position. Again the spring holds the handle and actuator in a stable position which is also guaranteed by the latch.

Figure 7: Operation Sequence of Smart Bypass Transfer

VI. SMART BYPASS COMPARED TO TRADITIONAL BYPASS

A theoretical component-based analysis of the Smart Bypass in manual operation compared to a traditional bypass will yield very similar results because it is dominated by the breaker reliability. However, because the phase checking feature eliminates the need for the internal bypass, and because these elements are both in series with the inverter, the Reliability of the path between the Inverter and the load is doubled.



However, this ignores the benefit of preventing operator error. If it is accepted that 50% of failures are related to operator error and that operator error is eliminated by protection features of the design, then combined with the improved inverter path, the failure rate should be reduced by2/3rds.

In addition to the Reliability improvement, the Availability improves by the reduced time to repair using Auto transfer (according to calculations, from about 5 x 9's to more than 7 x 9's). Typically, manually switching to bypass takes <5 minutes for an on-site technician, however it can be much longer for off-site technicians, especially for remote sites. For distribution type equipment like that used in cable the difference in customer satisfaction can be enormous. A short interruption can be tolerated, but extended issues are quickly escalated through the management hierarchy.

VII. SMART BYPASS COMPARED TO STATIC BYPASS

A common alternative to the internal bypass, especially for larger (non-modular) systems, is the static bypass. A static bypass incorporates semiconductor devices to transfer from inverter to utility within a quarter-cycle of the AC waveform. The key benefit is no interruption to the critical load, which would seem preferable to the "Smart Bypass" one second transfer delay.

Fundamentally however; a static bypass serves a different function and has a different implementation than a maintenance bypass. Firstly, a static bypass is intended to increase Reliability of the inverter system by creating a redundant path. To do this, it must be completely in parallel and independent and must include its own input and output breakers. For monolithic inverters this brings the MTBF from the 150,000 hours range to > 1M hours -- a huge benefit. However, a similar improvement is not possible for modular inverter systems which already achieve similar levels of reliability using redundant modules. One modular UPS manufacturer does include a static bypass circuit within each module, but this is thought to be more for transient load surge capability. Compared to a monolithic inverter static bypass, it does not provide a parallel path for the main input and output breakers.

Historically there have also been concerns about the use of a static bypass. For very critical applications UPS systems are always run in double-convert mode where the load is isolated from the AC source. Connecting the load to the utility to ride through transients is therefore not an ideal strategy. Secondly there have been cases of a Static Bypass failure cascading to the inverter system, exposing the reality that no two systems connected in parallel are truly independent, regardless of the calculations. It would therefore be recommended for a modular system to increase reliability using more redundancy (for example from N+1 to N+2) rather than incorporate a static switch.

Regardless of the above discussion, any system requires an isolating maintenance bypass for service, and the operator-proof protections of the Smart Bypass would benefit any installation.

VIII. SMART BYPASS COMPARED TO AUTOMATIC TRANSFER SWITCH

An Automatic Transfer Switch is another alternative to the Auto-transfer functionality of the Smart Bypass. These are typically used for switching the input source (for example from Generator to Utility) but could be also used for the output. The main advantage of an Automatic Transfer Switch is that they are motor driven and can be remotely controlled to cycle back and forth between two sources. The Smart Bypass in comparison is manually charged and can only perform the Inverter to Utility change once and then needs operator involvement. The trade-off in this case for the Smart Bypass are cost and Reliability. At ½ to 1/3rd the cost, and with far fewer components to fail, the increment cost of a Smart Bypass over a Traditional Maintenance bypass is simply more pragmatic.

IX. TESTING

Functional Testing

During the development process a sophisticated test platform was developed to monitor precise timing of the moving parts including breaker power contacts, breaker auxiliary contacts, actuator position, and handle position. This setup allowed for an exhaustive functional test protocol to identify and resolve potential causes of failure, and to optimize operating margin.

A typical mechanical transfer test is shown in Figure 8 below. The waveforms are: 60Hz AC (red), position transducer for actuator (cyan), actuator utility position (green), actuator inverter position (yellow). The total travel time of 40 milliseconds is typical for the 400A version of Smart Bypass currently under development. The overlap time is not shown but is approximately 5 milliseconds.

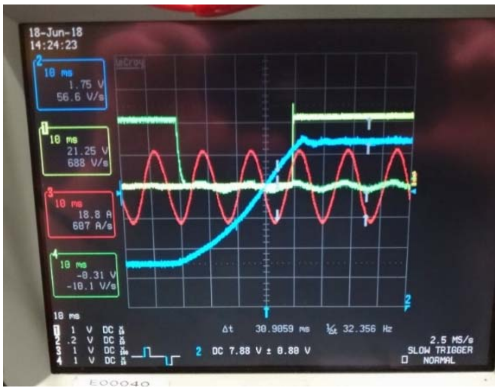


Figure 8: Typical Transfer Waveforms 400A Bypass

Cycle Testing

After functional testing was complete, several systems were subjected to cycle testing using a pneumatic actuator. The anticipated required cycle life assumed operation twice per month (including switch to and from bypass each cycle) for 20 years is ~500 cycles. The threshold for a critical transfer switch however is 10,000 cycles so this target was selected. Five (5) systems of both 100A and 250A capacity were assembled and tested, all terminated due to the same breaker failure mode. The cycle life ranged from 8,800-16,000 cycles, giving a 3 Sigma confidence interval of 980 cycles.

While this far exceeds the real anticipated use, due to the critical nature of this component along with risk aversion in the industry, another test program with a larger number of units is underway.

A second goal of the cycle test was to develop predictive maintenance capability. For this three gradual failure modes were detected: (1) the breaker reactive force decreases gradually as it nears end-of-life and suddenly upon failure, (2) the actuator friction decreases initially then increases very slowly, and (3) the actuator friction is much higher if improperly assembled. The controller monitors the actuator transit time (speed) and can predict/detect these failures.

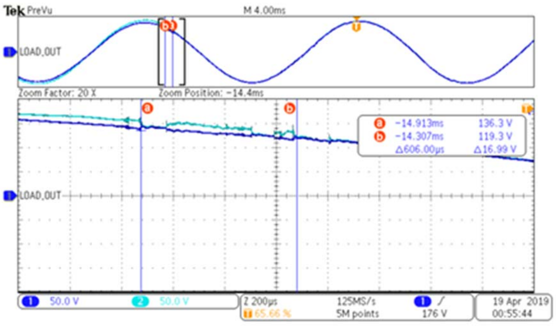


Figure 9: Make-before-Break Voltage Waveforms

The scope capture image shown in Figure 9 shows a bypass to inverter transition. The blue trace is the Load Output (originally connected to Utility) while the Cyan trace in the Inverter Output. Note that to make the transition visible, the Inverter Voltage was intentionally set differently from the Utility voltage. At point (a) the Inverter (Cyan) and Utility (Blue) merge, indicating that the inverter breaker contacts have first touched after which it takes approximately 600 microseconds for the the contacts to settle as per breaker specfcations. When the Utility Breaker opens, ~12 milleconds later, there is no visible transition.

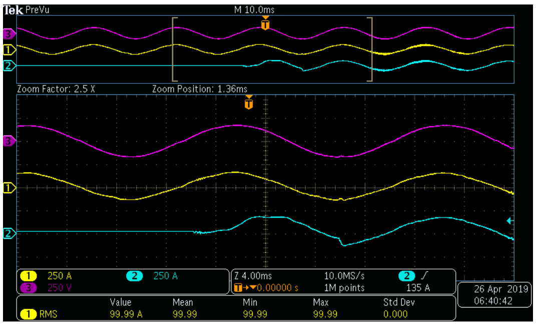
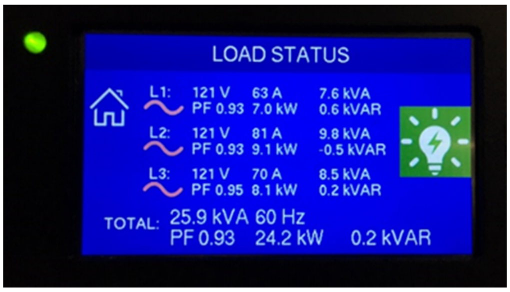


Figure 10: Make-before-Break Current Waveforms

The same transition is shown in Figure 10, this time with a focus on the current. The load voltage (pink) and current (yellow) remain constant. The Inverter current (Cyan) is initially zero and starts when the Inverter Breaker closes. The inverter current is irregular while both breakers are close as the inverter shares the load with the utility. After about 12 milliseconds the utility breaker opens and the Inverter supplies all of the load. When the utility disconnects the load, current settles for 0.5 milliseconds while the inverter control loop stabilizes.



LOAD STATUS

L1: 121 V 63 A 7.6 kVA
PF 0.93 7.0 kW 0.6 kVAR
L2: 121 V 81 A 9.8 kVA
PF 0.93 9.1 kW -0.5 kVAR
L3: 121 V 70 A 8.5 kVA
PF 0.95 8.1 kW 0.2 kVAR
TOTAL: 25.9 kVA 60 Hz
PF 0.93 24.2 kW 0.2 kVAR

Figure 11: AMPS HP2 Load at Enersys Burnaby Facility

Beta Testing

The technology is now being beta (field) tested:

- 250A Smart Bypass system has been in use at Alpha Burnaby location in Vancouver, Canada as part of the IT Backup system for 5 months
- 250A and 100A Smart Bypass systems have been installed in the EnerSys demo center in Suwannee, Georgia for more than 8 months.
- 100A Smart Bypass has been shipped to an external customer test facility for evaluation.

A number of integrated systems, including AMPS HP2 UPS systems, DC disconnects, 100A Smart Bypass, and rectifier system in a self-contained 19” box bay, are under development, while in parallel a rigorous test program continues in our EnerSys Burnaby lab.

X. FUTURE

While the technology is still being proven as a direct replacement for the existing Maintenance Bypass, other opportunities are being explored. For example, an Automatic Transfer Switch for low cost applications where manual reset would be acceptable.

XI. CONCLUSION

In this paper a pragmatic review of bypass systems has been presented and the Smart Bypass technology has been introduced. In order to safely repair any UPS system, it must be isolated from the utility source and load, and this inherently makes it a single point of failure. When reconfiguring power, either for maintenance but especially to restore a dropped load, there is significant stress on the technician. Though theoretically easy, executing the right sequence under these conditions has historically proven to be prone to error. The proposed technology takes a minimalist approach by adding error checking without decreasing the reliability of the underlying architecture. Although it requires a manual operation to recharge the actuating spring after each use, the simple switch mechanism is low cost and reliable. Furthermore, by integrating independent phase checking, the normally required internal bypass can be eliminated, thus creating an overall more reliable lower cost total system.

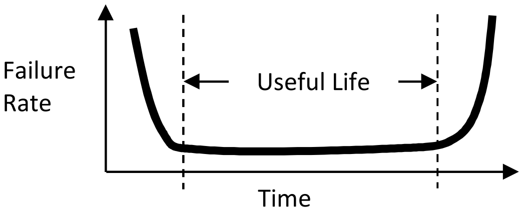
An advanced feature of the Smart Bypass is the semi-Automatic Transfer. Compared to a Static Bypass, it does not increase the system Reliability because there is a momentary interruption to the load. However, for remote sites, or any installation where a technician is not readily available, the automatic transfer can significantly improve Availability. Preliminary feedback from the market is that the most important benefit is reducing the stress on the repair technician, resulting in avoidance of the rapid call escalation that occurs when sites remain down.

Figure 12: 100A Smart Bypass, Armed for Auto Transfer with Handle Lockout Installed (wall mounted)

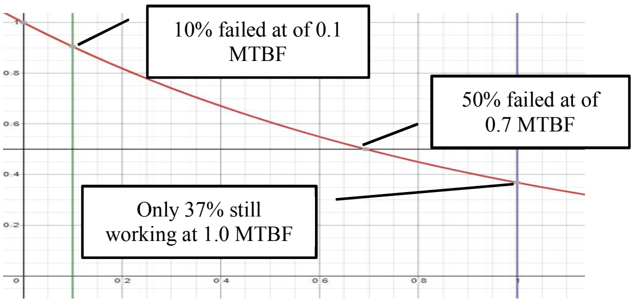
XII. CAVEATS ABOUT MTBF

In preparing this document I have fielded many questions about system Reliability and Availability. The biggest confusion is about MTBF, so I am including a few notes for the interested reader.

The common assumption is that MTBF is the expected time a product will last. There are three major problems with this assumption. Firstly, the MTBF only applies to stress related failures and is only significant during the "Useful Life" of a product, which is after defective component failure and before wear-out. It is a fact that something can have a very low failure rate yet relatively short useful life, for example a cell phone on a single battery charge.



The second challenge with MTBF is that is only applies to a population of devices. In the population, as devices fail there are fewer remaining, so the population follows an exponential curve and by the time 1 MTBF period elapses 63% of product has failed.



The third problem with MTBF is it is rarely an accurate measured value. Often it is a calculated estimate based on standard parts, but this assumes that design quality is constant. Theory is no substitute for testing or experience in this case.

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