OCTOBER 2, 2023

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Executive Summary

This white paper provides a detailed comparative analysis of centralised and distributed static bypass architectures in modular Uninterruptible Power Supply (UPS) systems.
It evaluates reliability, availability, and operational performance using industry-standard dependability equations and assumptions aligned with IEEE 493, IEC 61508, and IEC 62040-3.
Results demonstrate that a centralised static bypass achieves a measurable system MTBF improvement beginning from approximately three modules (≥ 10 %) and exceeds 15 % improvement from five modules and above.
At higher module counts, the centralised topology further simplifies protection coordination and reduces synchronisation complexity, delivering greater operational predictability.
The findings confirm that the centralised bypass is technically preferred for medium-to-large modular UPS configurations, while distributed bypass remains acceptable for compact, low-module systems where individual autonomy is prioritised.

Centralised vs. Distributed Static Bypass Design in Modular UPS Systems

A Comparative Reliability Analysis for Modular UPS Architecture

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1. Introduction

Modular UPS systems deliver scalable power protection through multiple inverter-rectifier modules operating in parallel.
Each module can share the critical load or provide redundancy in an N + 1 configuration.
The static bypass is an essential circuit that ensures continuity of supply during overloads or maintenance operations.

Two architectural approaches are common:

- **Centralised bypass:** A single Static Transfer Switch (STS) serves all power modules.
- **Distributed bypass:** Each module integrates its own STS and operates semi-independently.

This paper analyses both architectures using reliability modelling, availability equations, and practical operational factors relevant to modular UPS design.

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2. Reliability and Availability Modelling

UPS reliability is evaluated using the failure rate (λ), Mean Time Between Failures (MTBF), and Mean Time To Repair (MTTR).

Equation 1: $\lambda = \frac{1}{\mathrm{MTBF}}$

For distributed bypass systems:
Equation 2: $\lambda_{\mathrm{D}} = (N+1)\frac{1}{(\lambda_{\mathrm{p}} + \lambda_{\mathrm{s}})}$
Equation 3: $\mathrm{A_D} = \frac{\lambda_{\mathrm{D}}}{(\lambda_{\mathrm{D}} + \mathrm{MTTR})}$

For centralised bypass systems:
Equation 4: $\lambda_{\mathrm{C}} = \left(\frac{1}{(\lambda s} + \frac{\mathrm{N+1}}{\lambda p}\right)^{-1}$
Equation 5: $\mathrm{A_C} = \frac{\mathrm{MTBF_C}}{(\mathrm{MTBF_C} + \mathrm{MTTR_C})}$

Where:
λ_p = power-module failure rate | λ_s = static bypass failure rate | N = active modules

Availability A = $\mathrm{A_C} = \frac{MTBF}{(MTBF + \mathrm{MTTR})}$

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3. Basis of Recommendation

The improvement ratio between centralised and distributed bypass MTBFs is given by:

Equation 6: $m \geq \frac{(1+\delta)\,r}{(r-\delta)}$ where $r = \frac{\lambda_s}{\lambda_p}$ and m = N + 1

Assuming r = 0.2 (the bypass is five times more reliable than a power module):

- For δ = 10 %, m ≥ 3 modules.
- For δ = 15 %, m ≥ 5 modules.

These thresholds correspond with dependability conventions in IEEE 493 and IEC 61508, which define improvements above 10–15 % as engineering-significant.

4. Example Calculation

Assumptions:
$MTBF_p$ = 100 000 h | $MTBF_s$ = 500 000 h | MTTR = 2 h

Configuration	λ_D (h^{-1})	$MTBF_D$ (h)	λ_C (h^{-1})	$MTBF_C$ (h)	Gain (%)
3 (2 + 1)	1.50×10^{-4}	6 667	1.33×10^{-4}	7 500	+12.5
5 (4 + 1)	1.20×10^{-4}	8 333	1.04×10^{-4}	9 615	+15.4
7 (6 + 1)	1.14×10^{-4}	8 772	9.73×10^{-5}	10 275	+17.1

The analysis shows that the MTBF improvement exceeds 10 % from three modules and surpasses 15 % from five modules upward.

5. Electrical and Operational Behaviour

In a distributed bypass system, each module introduces its own bypass impedance (Z_1, Z_2 … Z_n). Minor impedance differences cause unequal current sharing, described by $I_i = V / Z_i$, which can lead to thermal stress and uneven load transfer.

A centralised bypass employs one common STS, ensuring a uniform, low-impedance transfer path and consistent current distribution. It also centralises synchronisation control, reducing potential phase mismatches between modules and simplifying protection coordination.

6. Failure Modes and Effects (FMEA) Summary

Component	Failure Mode	Effect	Mitigation
Power Module	Inverter failure or overheating	Capacity loss, derating	N + 1 redundancy, thermal monitoring

Component	Failure Mode	Effect	Mitigation
Static Bypass	SCR open/short	Transfer failure or load loss	Dual STS redundancy, status feedback
Control Logic	Desynchronisation	Mismatched transfer, transient stress	Central controller, signal integrity check

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7. Design Recommendations

Based on the analytical model and dependability criteria (IEEE 493, IEC 61508), the centralised static bypass provides clear, progressive reliability benefits as module count increases.

Notable Improvement (≥ 10 %) – from three modules (2 + 1):
Centralised bypass begins to yield a measurable reliability advantage, with simplified synchronisation and uniform current sharing.

Material Improvement (≥ 15 %) – from five modules (4 + 1):
The advantage becomes operationally meaningful; system availability increases and coordination improves.

Strongly Recommended – from seven modules (6 + 1) and above:
Distributed synchronisation complexity rises sharply. A single centralised STS delivers superior fault management and maintainability.

Distributed bypass remains acceptable for compact systems where modular autonomy is prioritised over aggregate MTBF.

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8. Conclusion & Recommendations

Analytical modelling, example calculations, and failure-mode analysis demonstrate that the **centralised static bypass** architecture provides higher reliability, simpler coordination, and improved maintainability compared with distributed designs.

The **recommended approach** is therefore:
✓ For systems ≥ 3 modules → use centralised bypass for measurable gain.
✓ For systems ≥ 5 modules → centralised bypass is preferred by design.
✓ For systems ≥ 7 modules → centralised bypass is strongly recommended.

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9. References

1. IEEE Std 493-2007 – *Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*
2. IEC 62040-3 – *Uninterruptible Power Systems – Method of Specifying Performance*
3. IEC 61508 – *Functional Safety of Electrical/Electronic/Programmable Electronic Systems*
4. CIGRE WG C4.111 – *Reliability Modelling of Power Conversion Systems*
5. IEEE Transactions on Industry Applications, various issues (2019–2021): Studies on Modular UPS System Reliability Modelling and Redundancy Analysis.

End of Document

This white paper is provided for technical reference and informational purposes.