SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Comparative Analysis of 400 V AC and Bipolar 800 V DC Power Distribution Architectures for a Hyperscale Data Center

TESI MAGISTRALE IN ELECTRICAL ENGINEERING – INGEGNERIA ELETTRICA

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1. Context and Technical Motivation

This work compares two power distribution architectures for a large-scale data center: a conventional 400 V AC system and a bipolar ±400 V DC system. The purpose is to evaluate how the choice of architecture affects conductor sizing, copper usage, electrical losses, and system reliability.

The comparison is carried out under the same design assumptions, including routing lengths, redundancy philosophy, and operational load conditions. The intention is not to redesign the facility, but to assess how the distribution concept alone influences technical and quantitative performance.

In high-power data centers, the Low Voltage (LV) distribution stage represents a significant share of material usage and contributes to both energy losses and system unavailability. Even moderate improvements at this level can result in meaningful reductions in copper consumption, operating energy, and overall system complexity. For this reason, a structured and measurable evaluation is required, as previous comparative studies have shown that differing modeling assumptions can significantly influence the perceived efficiency advantage [1].

Additionally, DC distribution is inherently compatible with renewable energy sources and energy storage systems, since technologies such as photovoltaic generation, battery storage, and fuel cells are DC-native and require fewer conversion stages when integrated into a DC backbone [2].

The analysis in this study is based on three main aspects:

1. Conductor sizing and copper usage**:** including cross-section selection, copper volume, total mass, and cable cost.
2. Electrical loss calculation: using real operational current and power usage data over one full year to estimate annual energy losses.
3. Availability and reliability assessment: performed through Reliability Block Diagram (RBD) modeling using standard failure rate data for 5 years.

The study focuses strictly on technical and quantitative evaluation. Protection coordination, regulatory aspects, and detailed converter design are outside the scope of this work.

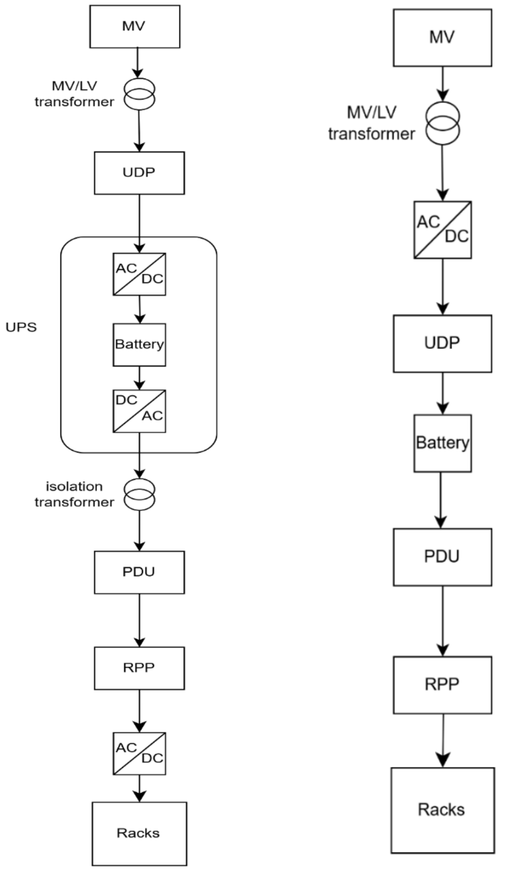
2. System Definition

This summary compares existing 400 V AC low-voltage distribution architecture with a proposed bipolar ±400 V DC architecture, using a consistent system boundary and a common set of design assumptions.

2.1 Architecture boundary and distribution levels

The analysis starts at the MV/LV transformer and follows the internal low-voltage distribution path down to the RPP level, which is considered the last common distribution node before the final loads. The distribution is modeled as a hierarchical structure with multiple bus levels, where each level represents a bus supplying several downstream branches.

Figure 1 illustrates the simplified AC and DC distribution architectures considered in this study.



(a) Current AC configuration

(b) Proposed DC configuration

Figure 1. Simplified AC and DC architecture

2.2 Main differences between the AC and DC architectures

Within the same boundary, the proposed DC configuration differs from the AC model in three key points:

1. The AC UPS system is replaced by a DC battery system.
2. The isolation transformer is removed in the DC model, since galvanic isolation is already provided upstream at the MV/LV transformer level.
3. The AC/DC conversion stage is relocated from locally before each load to immediately after the MV/LV transformer.

As a result, DC architecture reduces the number of downstream conversion stages and simplifies the power path feeding the IT load.

2.3 Voltage level and load interface

The DC architecture is implemented as a bipolar ±400 V system (800 V DC pole-to-pole). This configuration is selected because it reduces current for a given power, while maintaining flexibility and fault tolerance with the possibility of single-pole operation.

In the modeled DC case, IT loads are assumed to operate at 800 V DC in the DC architecture, consistent with the system boundary used in the thesis.

2.4 Common assumptions for a fair comparison

To ensure a consistent comparison, the two architectures are evaluated under identical design criteria:

- Redundancy assumptions: 2N for the IT load and 2oo3 (3-to-make-2) redundancy for upstream sections, applied consistently in both AC and DC cases.
- Cable modeling: sizing is performed using single-core cable assumptions, with FG7M1 (0.6/1 kV AC) adopted for the AC configuration and FG16R16 (1.5 kV DC) for the DC configuration. Neutral and protective earth conductors are also included consistently.
- Load allocation: For cable sizing the load is distributed homogeneously among identical devices at each level, for design purposes.

3. Methodology

The comparison between the AC and DC architectures is based on a structured and quantitative methodology.
The evaluation is organized into three main components: conductor sizing and copper quantification, annual electrical loss calculation, and availability and reliability assessment.

3.1 Conductor Sizing and Copper Quantification

Cable cross-sections for the DC structure are selected according to two criteria: ampacity limits and maximum allowable voltage drop.

For each distribution branch, the design current is calculated from the assigned load power. The selected cross-section must satisfy both the thermal current-carrying capacity, derived from the manufacturer ampacity table, and a steady-state voltage drop limit of 1.6% per distribution level.

To evaluate the impact of sizing philosophy two different approaches are adopted:

- Minimum possible CSA: where the smallest cross-section satisfying both ampacity and voltage drop constraints is selected for each branch.
- Constant current density: where conductors are sized to maintain a uniform current density across comparable branches in AC.

Once the cross-sections are defined, the key quantities are computed:

- Total cable mass
- Estimated material cost

Neutral and PE conductors are modeled consistently to ensure structural rather than different safety assumptions.

3.2 Annual Electrical Loss Assessment

Electrical losses are calculated using real operational current data measured over one full year.

For each branch, resistive losses are computed using:

$$P_{loss} = I^2 R$$

where the resistance is derived from the selected conductor cross-section, operating temperature, and installation length.

By integrating the current values over the year 2024, the total annual energy loss (MWh/year) is obtained for both architectures. This approach avoids the use of constant-load assumptions and reflects realistic operational behavior.

The resulting annual energy losses are later translated into environmental impact and operational cost implications.

3.3 Availability and Reliability Modeling

The availability and reliability analysis is performed using RBDs to represent the functional structure of both architectures.

Each component in the distribution path (including transformers, inverters, rectifiers, batteries, busbars, and cables) is modeled as a reliability block characterized by:

- Mean Time to Repair (MTTR)
- Mean Time Between Failures (MTBF)

Standard reference data are adopted in accordance with IEEE 493 (Gold Book) assumptions [3].

The availability is calculated as:

$$A = \frac{MTBF}{MTBF + MTTR}$$

In addition to steady-state availability, reliability is evaluated using the exponential reliability model:

$$R(t) = e^{-\lambda t}$$

where $t = 5$ years.

For series-connected components, the values are computed as the product of individual components. For parallel and k-oo-n arrangements, equations 1 and 2 are adopted, respectively.

$$A_{parallel} = 1 - \prod_{i}(1 - A_i) \quad (1)$$

$$A_{koon} = \sum_{i=k}^{n} \binom{n}{i} A^i (1 - A)^{n-i} \quad (2)$$

Special attention is given to how architectural simplifications influence reliability and availability:

- The removal of the downstream transformer in the DC configuration reduces the number of series elements.
- The relocation of the AC/DC converter modifies the failure probability within the system.
- The alteration from a UPS system to a battery directly impacts failure rates.

The RBD approach allows a clear structural comparison between the AC and DC configurations and quantifies how architectural differences affect long-term operational continuity.

4. Main Results

4.1 Copper Usage and Material Impact

The conductor sizing process shows a clear reduction in required copper when adopting the bipolar ±400 V DC architecture:

Configuration	Cable Mass [tons]	Cable cost [M€]
AC	536.2	7.26
DC - minimum CSA	298	4.8
DC - constant J	418.2	5.4

Table 1. Material impact

The results confirm that the architectural difference alone, without changing redundancy philosophy or routing assumptions, produces a significant material impact.

4.2 Electrical Losses and Annual Energy Impact

The annual distribution losses are evaluated for both AC and DC architectures, considering two different criteria for the DC system.

AC Architecture: For the 400 V three-phase AC system, losses are calculated for all active conductors within the defined distribution boundary. This includes:

- Phase conductors
- Neutral conductors, where applicable

The neutral current is determined from the measured phase currents, allowing the model to capture the effect of load imbalance.

The total annual distribution loss for the AC architecture is: 3278 MWh/year

This value represents the cumulative losses of the complete low-voltage distribution system within the study boundary.

DC Architecture

For the bipolar ±400 V DC, losses are evaluated under two different conductor sizing criteria to assess the influence of design philosophy on total annual losses.

1) Minimum CSA Criterion: Under this criterion, the total annual DC distribution loss is:

1102 MWh/year

2) Constant Current Density Criterion: This approach results in the same cross-sections as the AC model and leads to annual loss of:

693 MWh/year

The constant-J approach selects larger conductor cross-sections than the minimum-CSA solution, reducing resistance and therefore annual resistive losses.

Comparative Assessment

For a clear comparison, the calculated annual losses and the corresponding operational costs are summarized in Table 2, with cable material prices extracted from "ComCavi" online shop in October 2025.

Configuration	Total energy loss [MWh]	Average power loss [kW]	Annual Cost [k€]
AC	3278	373.2	593.4
DC - minimum CSA	1102	125.4	199.5
DC - constant J	693	78.93	125.4

Table 2. Annual losses and costs[1]

The substantial reduction in annual losses observed in the DC configurations is primarily due to three factors: (I) the higher effective distribution voltage (800 V pole-to-pole), which reduces current levels and therefore I^2R conductor losses; (II) the absence of neutral current and phase imbalance effects.

In addition to the direct electricity cost reduction, the lower distribution losses of the DC architecture reduce the facility energy overhead and therefore contribute to a lower effective PUE (from 1.35 to 1.32), while also decreasing the associated environmental impacts (more than 500 tons of CO_2 emissions per year).

4.3 Availability and Reliability Results

The availability and reliability of the AC and DC architectures are evaluated using RBD modeling. Each component within the defined distribution boundary is represented by a reliability block characterized by its failure rate and repair time. Identical redundancy assumptions are applied to both configurations (2N at IT level and 2oo3 upstream).

4.3.1 Steady-State Availability

Both architectures satisfy high-availability design targets, but the calculated results show a measurable improvement in the DC configuration. The AC architecture results in expected downtime on the order of hundreds of seconds per year, although the DC architecture reduces this value to the order of milliseconds per year within the modeled distribution boundary.

This improvement is structurally driven by:

- Removal of the downstream isolation transformer in the DC configuration
- Reduction in the number of series-connected components
- Simplification from UPS system to battery

Since availability in series systems is multiplicative, even a modest reduction in

[1] Annual energy losses are computed using 2024 operating hours (8784 h, leap year).

component count leads to a substantial decrease in cumulative unavailability.

4.3.2 Five-Year Reliability

The five-year reliability values obtained from the model are:

- AC architecture: 97.747%
- DC architecture: 99.891%

The DC configuration therefore exhibits a higher probability of uninterrupted operation over a five-year horizon.

The improvement reflects architectural simplification and lower failure probability in the DC power path.

4.3.3 Engineering Interpretation

Beyond the direct numerical improvement, the architectural simplification of the DC configuration also opens the possibility for adopting alternative connection schemes, resulting in reduced component count and simplified current paths.

Such connection methods are more complex to implement in AC low-voltage systems due to synchronization, protection, and circulating currents.

4.4 Overall comparison

Figure 2 presents the normalized comparison between the 400 V AC architecture and the bipolar ±400 V DC configurations, with the AC system taken as the 100% reference.

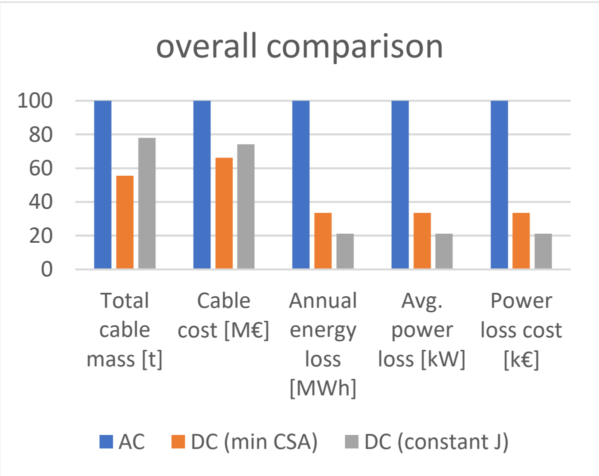


Figure 2. Comparison between AC and DC structures

Both DC sizing approaches reduce total cable mass, cable material cost, and distribution losses compared to AC. The constant current density (J) criterion results in slightly higher cable mass and cost compared to the minimum possible CSA approach, due to higher conductor sizing. However, it achieves lower annual energy losses and reduced loss-related costs.

Overall, the chart confirms that the DC architecture provides significant improvements in both material usage and efficiency, regardless of the sizing strategy adopted.

In addition, the reliability and availability comparison is shown in Figure 3.

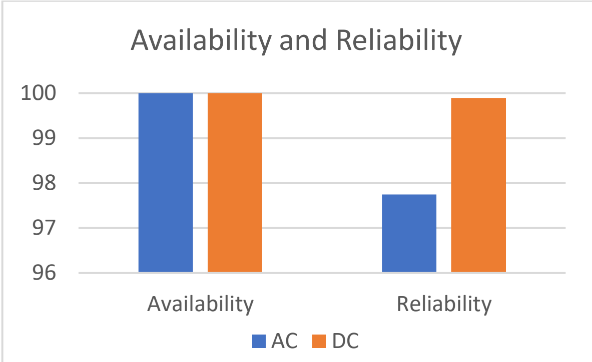


Figure 3. Availability and reliability comparison

Figure 3 shows that both systems achieve high availability levels, close to 100%, reflecting the redundancy assumptions adopted in the design. Although the percentage differences appear small, the DC configuration includes a higher number of "nines" in its availability figure. This seemingly minor numerical increase translates into a substantial reduction in expected downtime. This feature is crucial in high-availability environments such as data centers.

On the other hand, the improvement in reliability is more pronounced over the five-year horizon, where the DC configuration shows a higher probability of uninterrupted operation (more than 2%).

5. Limitations and Modeling Assumptions

The results presented in this study are derived under clearly defined system boundaries and modeling assumptions.

First, the economic evaluation is limited to cable material cost and copper usage. Installation labor, containment systems, protection devices, transportation, taxes, and lifecycle maintenance costs are not included. In addition, potential cost differences in switchgear and DC-rated protection equipment are not explicitly quantified, and the current lack of full standardization in DC protection and distribution components may further influence practical implementation and cost assessment [4]. However, ongoing technological and standard development in DC components may reduce this gap over time.

Second, the electrical loss calculations consider resistive losses based on measured operational current data. Harmonic distortion effects in AC systems and detailed converter efficiency modeling are outside the scope of this work.

Third, protection coordination, short-circuit studies, and dynamic fault analysis are not modeled.

Finally, the reliability analysis is based on standard component failure rate data and steady-state statistical modeling. Real-world performance may vary depending on maintenance strategy, environmental conditions, and manufacturer-specific characteristics. Nevertheless, identical assumptions are applied to both architectures, ensuring a structurally consistent comparison.

6. Conclusions and future work

This work has provided a structured and quantitative comparison between a conventional 400 V AC distribution architecture and a bipolar ±400 V DC architecture within a large-scale data center environment.

The results demonstrate that the DC configuration achieves:

- Significant reduction in cable mass and material cost
- Substantial decrease in annual distribution losses
- Lower expected unavailability time
- Improved long-term reliability performance

These improvements are primarily driven by architectural simplification, reduced current levels, and a lower number of series-connected components in the distribution path.

Beyond the quantified benefits, the DC architecture enables additional structural flexibility. The simplified current paths create the opportunity to adopt alternative connection schemes such as ring or meshed topologies, which may further enhance redundancy and resilience. Such configurations are more complex to implement in conventional AC systems due to synchronization and protection constraints.

Beyond the scope of the present comparison, further work may focus on additional improvements aimed at enhancing overall data center performance. These include the integration of waste heat recovery systems, adoption of advanced cooling technologies, incorporation of next-generation energy storage solutions, and optimization of UPS and battery operating strategies.

Moreover, architectural flexibility and enhanced availability offered by DC distribution could support the implementation of innovative grid-interactive features, improved load management strategies, and enhanced energy efficiency at facility level.

Such developments would contribute to a more sustainable and resilient data center infrastructure, extending the benefits of architectural optimization beyond distribution efficiency alone.

References

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