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Examining Future Data Center Power Supply Infrastructures

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ABSTRACT :

The rapid expansion of data processing in the past few years has created a massive demand for data center installations worldwide, and energy conservation strategies have become crucial. The enormous increase in data center installations and their significant contribution to global energy consumption require the implementing of energy saving techniques and participating in supporting the power grid. This thesis presents an architecture-level review of power distribution systems in data centers, examining AC, DC, and hybrid architectures with a focus on enhancing efficiency and reliability One of the key areas that can be enhanced to improve the overall energy efficiency of data centers and the provision of ancillary services for the grid is the Uninterruptible Power Supplies (UPS). This thesis reviews the current state-of-the-art power supply systems and topologies mainly used in data centers and aims to identify ways to increase the overall energy efficiency of data center power supply systems. Moreover, this work presents a detailed analysis of the power supply losses and proposes systems that can improve the conversion efficiency of UPS systems under various loading conditions. The performance metrics in the data center business need to be more accurate. Therefore, the variety of performance metrics, considering energy efficiency, sustainability, reliability and costs, are analysed in the thesis. The conclusion of the thesis wraps up the findings and provides guidelines for planning the power supply infrastructure for various conditions.

KEYWORDS: Data Center, Power Supply, Power Distribution Infrastructures/Architectures

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Abbreviations

AC	Alternating Current
ASICs	Application-Specific Integrated Circuits
ATS	Automatic Transfer Switch
BDCBB	Battery Distribution Circuit Breaker
BEV	Battery Electric Vehicle
CPU	Central Processing Unit
CUE	Carbon Usage Effectiveness
CAES	Compressed Air Energy Storage
FES	Flywheel Energy Storage
DC	Direct Current
DCCBs	Direct Current Circuit Breakers
DCeP	Data Center energy Productivity
DCIE	Data Center Infrastructure Efficiency
DCs	Data Centers
EPA	Environmental Protection Agency
ESI	Energy Sectors Integration
EU	European Union
FAP	Fuse Alarm Panel
GEC	Green Energy Coefficient
HVAC	Heating, Ventilation, and Air Conditioning
HVDC	High Voltage Direct Current
ICT	Information and Communication Technology
IEA	International Energy Agency
ITEE	IT Equipment Energy Efficiency
LVAC	Low Voltage Alternating Current
Li-ion	Lithium-ion
LHES	Liquid Hydrogen Energy Storage
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance

MTTR	Mean Time To Repair
MV	Medium Voltage
Nickel-Cd	Nickel-Cadmium
PDU	Power Distribution Unit
POL	Point of Load
PFC	Power Factor Corrector
PSU	Power Supply Unit
PUE	Power Usage Efficiency
PV	Photovoltaic
PHES	Pumped Hydro Energy Storage
PSB	Power-to-Solid Battery
RES	Renewable Energy Sources
SST	Solid-State Transformer
STC	Switched Tank Converter
SHS	Superconducting Magnetic Energy Storage
SMES	Superconducting Magnetic Energy Storage
UPS	Uninterruptible Power Supply
UESs	Urban energy systems
VR	Voltage Regulator
VRLA	Valve Regulated Lead-Acid (battery)
VRB	Vanadium Redox Battery
WUE	Water Usage Effectiveness
ZVS	Zero Voltage Switching
Zn-Br	Zinc-Bromine

1 Introduction

Digital information management has become essential entity in preserving the standard operation of educational, governmental, businesses, and communication networks with the growth of internet business. Typically, a data center refers to a physical facility that centralizes the activities of processing, storing, transmitting, and exchanging information under controlled conditions (Shao et al., 2022).

The significant growth in both the number and scale of data centers is becoming increasingly apparent. Economies of scale render large, hyper-scale data centers as the most economically viable option for cloud service providers. Predictions suggest that by 2030, data centers could consume up to 13% of global electricity (Andrae & Edler, 2015). This expansion introduces new challenges in power distribution, given that data centers represent some of the most significant and power-intensive demands on electrical grids. Enhancing the efficiency of power distribution within these centers could lead to substantial reductions in both energy consumption and operational costs. Furthermore, since data centers support crucial IT operations, power disruptions can incur considerable expenses. Therefore, there is a pressing need for innovative strategies to improve the efficiency, reliability, and cost-effectiveness of data center power distribution systems.

Conventional Low Voltage Alternating Current (LVAC) systems, which supply power to server rooms, require numerous devices and extensive cabling, increasing economic expenses and the likelihood of power failures. Proposals for data center architectures suggest potential remedies, particularly emphasizing the utility of Direct Current (DC) systems for IT loads that inherently operate on DC voltage. DC systems offer advantages over AC systems by having fewer stages of power conversion, which enhances efficiency and minimizes failure risks (Shrestha et al., 2018). Additionally, DC cables are capable of carrying more current than equivalently sized AC cables, offering a reduction in capital expenses (L. Chen et al., 2021). Medium Voltage (MV) distribution systems have also been proposed as solutions to address these challenges, promising benefits such as smaller spatial requirements, lower transmission losses, and enhanced reliability (Y. Chen et al., 2022).

1.1 Background

Infrastructure of data center are comprised of physical and logical components that are responsible for its operations. The core components in data centers are power supply, power distribution, storage systems, servers and their operation, networking Infrastructure, cooling and heating systems, electronic equipment for data processing, and communications networking. With the evolution of digital technology, data centers are becoming bigger and they are consuming a lot of energy for that efficient and sustainability are very important factors to achieve for green transition.

1.1.1 Data center power distribution architecture

A typical data center power supply architecture is basically consisting of power distribution and networking architecture. One of the key aspects of data center design and operation is power distribution, which involves delivering electricity from the utility level to the facility level and then to the rack level. Power distribution affects the performance, reliability, efficiency and cost of data centers. Therefore, it is important to understand the different levels of power distribution and their challenges and opportunities.

As illustrated in Figure 1, the power distribution architecture within a data center is organized into various levels, including the utility level, facility level, and rack level. This architecture encompasses a range of components, such as the power grid, transformers, switchgears, backup generators, uninterruptible power supplies (UPS), automatic transfer switches (ATS), batteries, power distribution units (PDUs), power supply units (PSU), cooling systems, multiple server racks, and other miscellaneous loads, including lighting. In the power sector of a data center, essential processes such as the conversion of voltages between AC (and DC, distribution wiring, and rectification are carried out to adjust voltages for their intended applications. On the networking side, data is digitally stored, processed, and then communicated between different servers, ensuring efficient information management and exchange. Data centers are usually classified into three sections utility level, facility level, and rack level. as illustrated in Figure 1 (Pratt et al., 2007).

At the utility level, data centers receive power from the grid or other sources, such as renewable energy or on-site generation. The utility power is typically delivered at a high voltage (e.g., 11 kV or 33 kV) and then stepped down by transformers to a medium voltage (e.g., 415 V or 480 V) suitable for the facility level. The utility power may also be conditioned by devices such as power factor correction units, harmonic filters or voltage regulators to improve its quality and stability.

At the facility level, data centers distribute power from the medium voltage transformers to the various loads within the building, such as IT equipment, cooling systems, lighting and security systems. The facility level power distribution may include switchgear, busbars, panel boards, UPS systems and backup generators. The UPS systems provide backup power in case of utility power failure and also protect the IT equipment from power disturbances such as surges, spikes, sags or outages. The backup generators provide long-term backup power in case of prolonged utility power outage and are usually fueled by diesel or natural gas. Traditional power systems within data center facilities primarily utilize Alternating Current (AC) at the facility level. However, there is a growing trend towards adopting Direct Current (DC) systems. This shift is attributed to the reduced number of conversion stages required by DC systems, enhancing their efficiency (Nabih & Li, 2021, 2023).

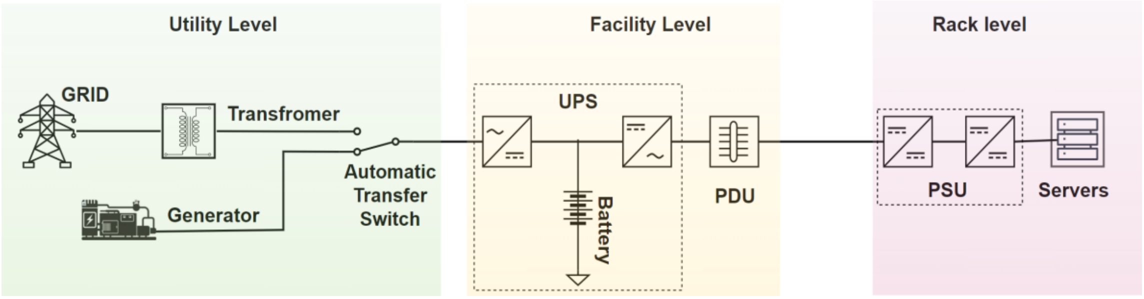

Figure 1. Typical Data Center

At the rack level, data centers distribute power from the facility level UPS systems to the individual servers through voltage regulators and PSUs, storage devices and networking equipment within the racks. The rack level power distribution may include PDUs, PSUs, rack-level UPS systems, branch circuit monitoring systems and intelligent outlets. The rack mostly in DC power systems and it can be single stage or two stage conversion method (M. H. Ahmed et al., 2020, 2021). The PDUs provide multiple outlets for connecting IT equipment and may also offer features such as metering, switching, monitoring and remote control. The rack-level UPS systems provide additional backup power for critical IT equipment within the rack. The branch circuit monitoring systems measure the power consumption of each branch circuit within the rack and provide data for capacity planning and energy management. The intelligent outlets enable individual control and monitoring of each IT equipment within the rack.

1.1.2 Why data centers are important?

In the modern digital era, data has become an invaluable asset, underpinning virtually every aspect of our lives. From powering online commerce and social media interactions to enabling scientific breakthroughs and fostering innovation, data is the lifeblood of our increasingly interconnected world. And at the heart of this data-driven revolution lies a crucial infrastructure called data centers.

Data centers are sophisticated facilities designed to store, manage, and process vast amounts of data efficiently and securely. They house a collection of powerful computers, servers, storage systems, and networking equipment, all interconnected to form a robust and scalable infrastructure. These centers are often strategically located to provide high-speed internet access and reliable power, ensuring that critical data remains accessible and protected at all times.

The significance of data centers extends far beyond their role in storing digital information. They play a pivotal role in enabling various essential services, including:

- **E-commerce and online transactions**: Data centers facilitate the efficient functioning of e-commerce platforms, enabling businesses to manage a large number of online orders and financial transactions. They guarantee the continuous operation of websites, allowing clients to effortlessly view products, make transactions, and maintain their accounts (Al Kez et al., 2022).
- **Social media and communication platforms:** The vast majority of social media interactions and messaging services rely on data centers. These centers handle the massive influx of data generated by billions of users, ensuring that messages are delivered promptly, connections remain stable, and platforms remain accessible (Velkova & Plantin, 2023).
- **Cloud computing and web services:** Data centers are the backbone of cloud computing, providing the infrastructure for businesses and individuals to access computing resources and data storage remotely. They enable cloud-based applications, such as email, productivity tools, and enterprise software, to function seamlessly (Katal et al., 2023).
- **Scientific research and innovation:** Data centers are essential for scientific research, enabling the processing and analysis of large datasets generated by scientific instruments and experiments. They support research in fields such as genomics, climate science, and astrophysics, leading to ground-breaking discoveries and technological advancements (Edwards et al., 2024).
- **Support for smart cities:** As smart cities flourish amidst rapid urbanization and information and communication technology development, the demand for building more data centers is rising. They are essential for maximizing the net benefits and remaining “green” (Lam et al., 2020).
- **Economic Impact**: Data centers have a significant economic impact. They are seen as an investment asset by some enterprises, while others use data center services on a co-location basis. The real estate costs associated with data centers can affect their success to a great extent (Lam et al., 2020).
- **Infrastructure for large digital corporations:** Large digital corporations such as Amazon or Google are expanding their role in urban infrastructural development,

including data centers. This expansion necessitates research to understand and explain this phenomenon(Bast et al., 2022).

- **Challenges of Urban Governance:** Data centers present challenges of urban governance. They have a high demand for energy and water, competing with local residents for these resources. The uneven distribution of data centers can invoke inter-county competition for tax revenue, in addition to access to the water, power, and land resources that data centers require (Bast et al., 2022).

The importance of data centers is further emphasized by their continuous growth and expansion. As the volume of data generated and consumed increases exponentially, the need for more powerful and scalable data centers is becoming increasingly pressing. This trend is driving innovation in data center design, management, and energy efficiency, as organizations strive to optimize these facilities to meet the demands of a data-intensive future.

1.1.3 Why Data Center Energy Consumption matters?

The escalating energy demands of data centers have become a critical issue, driven by the rapid expansion of cloud computing and the resulting escalation in data center activities. Developing energy consumption models for the various components within a data center is crucial for optimizing the design of its internal systems and minimizing its overall energy consumption. The effectiveness and dependability of data centers pose technical challenges that directly affect the service quality delivered to users(Bast et al., 2022; Cao et al., 2022; Dou, 2017).

To address these challenges, research has delved into various strategies for managing energy efficiency within cloud data centers. These strategies employ a range of approaches, including machine learning algorithms, heuristic techniques, metaheuristic methods, and statistical analyses. They aim to predict CPU utilization, detect states of underload or overload, and select, migrate, and place virtual machines efficiently. These efforts are geared towards optimizing resource allocation and enhancing energy efficiency.

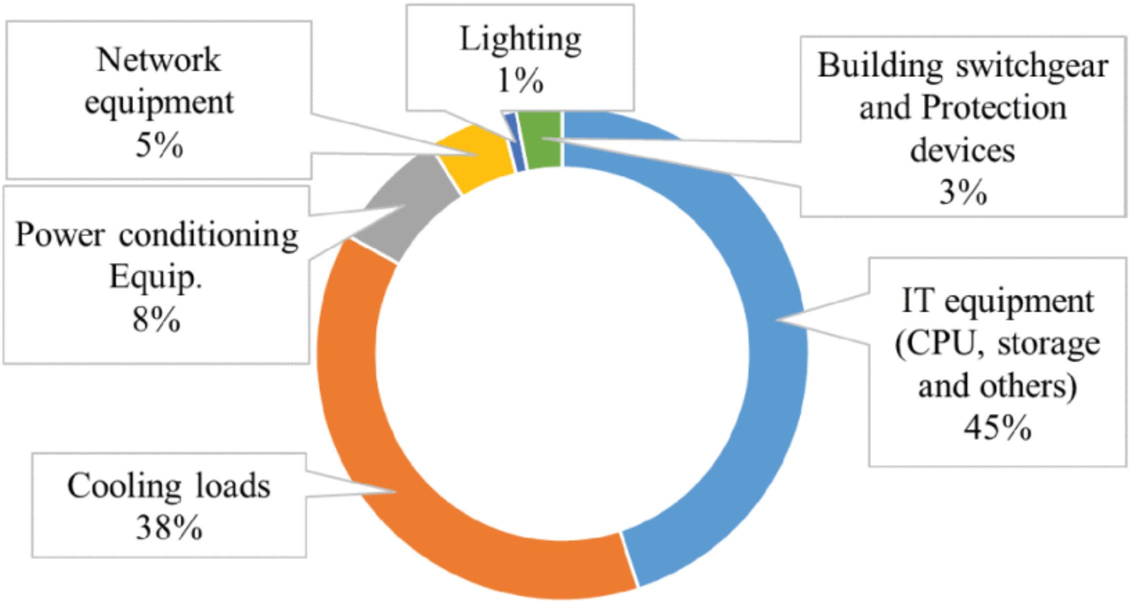

Figure 2. Analysis of power consumption proportionality in data center (K. M. U. Ahmed et al., 2021)

Moreover, the energy usage of data centers has implications beyond financial costs, posing significant environmental concerns. Data centers represent a major and growing sector of energy consumption within the economy and are a notable contributor to CO2 emissions. Therefore, improving the energy efficiency of data centers is imperative, not only to mitigate financial burdens but also to lessen environmental impacts, such as air pollution, greenhouse gas emissions, and the water usage associated with electricity production(Cao et al., 2022).

Constructing a precise representation of a data center's power consumption, whether at the overall system or individual component level, is a challenging undertaking. The power consumption of a data center is determined by various elements such as in Figure 2, including the hardware and internal infrastructure specifications, computational workloads, the applications utilized by the data center, and the cooling requirements, which are difficult to measure precisely. (Berezovskaya et al., 2020; P. C. Huang Benedetta; Zhang, Xingxing; Shen, Jingchun; Löfgren, Isabelle; Rönnelid, Mats; Fahlen, Jan; Andersson, Dan; Svanfeldt, Mikael, 2020). Furthermore, the power consumption of the IT load gear, the cooling system, and the power conditioning infrastructure of the data center are all interconnected. (Tatchell-Evans et al., 2017). Developing power utilization models at the component level facilitates tasks such as acquiring new equipment, strategizing system capacity, and growing resources, among other benefits.

1.1.4 Energy consumption in Data Center

The proliferation of data centers worldwide is consuming a significant amount of electricity and generating a substantial amount of heat relative to energy consumption. (Cao et al., 2022). It is becoming very serious issue in terms climate change and sustainability.

The International Energy Agency (IEA) has estimated that worldwide electricity consumption by data centers in 2022 ranged from 240 to 340 terawatt-hours (TWh), making up approximately 1 to 1.3% of the total global electricity demand (IEA, 2023). This estimation does not include the energy consumed for cryptocurrency mining, which was projected to be around 110 TWh in 2022, contributing to 0.4% of the yearly global electricity usage. In the United States, data centers accounted for an energy consumption of 91 billion kilowatt-hours (kWh) in 2013, with an anticipated increase to 140 billion kWh by 2020 (Shao et al., 2022).

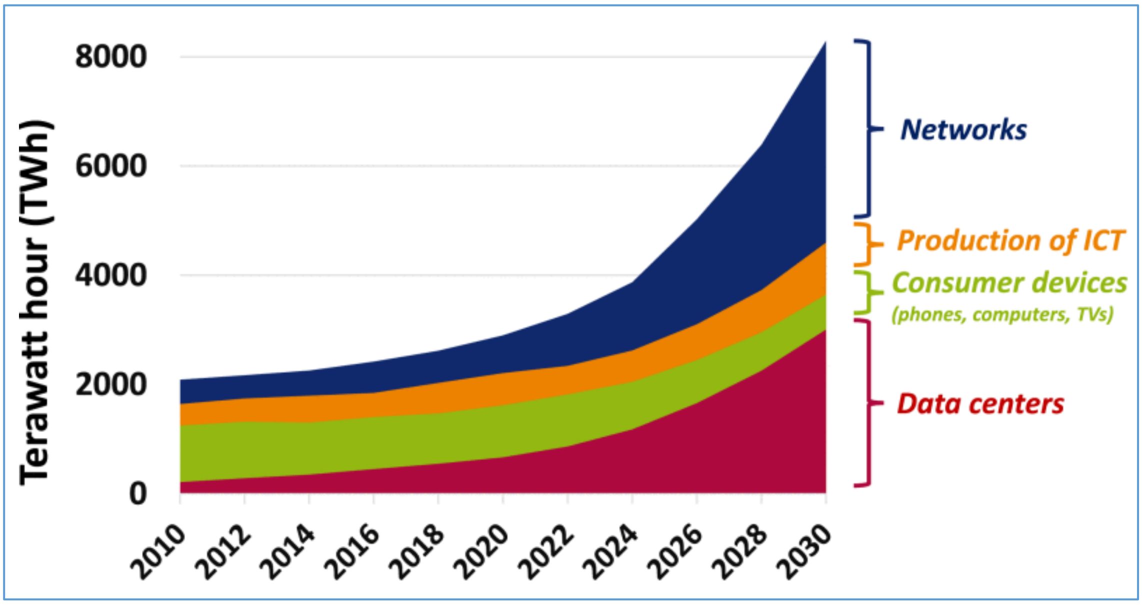

Figure 3. Energy forecast of ICT electricity consumption (Nabih & Li, 2023)

The growing reliance on cloud computing services has resulted in a significant increase in investments in data center infrastructure, with the annual global spending exceeding $200 billion (Nabih & Li, 2023). A considerable part of this investment is allocated towards the physical infrastructure needed for power supply, cooling, and space for server machines. A report featured in Nature magazine (Jones, 2018) forecasts that the total electricity consumption of the information and communication technology (ICT) sector is projected to reach 8000 terawatt-hours (TWh) by 2030, as illustrated in Figure 3. This figure is expected to constitute approximately 20% of worldwide electricity usage. Within this context, data centers are anticipated to represent about 40% of the ICT sector's energy consumption. Prompted by these trends, there has been a push towards improving the cost efficiency of data center development. This effort is focused on reducing the upfront costs associated with construction or enhancing the power usage effectiveness (PUE) to diminish operational expenditures.

1.1.5 Carbon Emissions

Data centers are undergoing rapid expansion, serving as foundational support for the fourth industrial revolution and the driving force behind the upcoming digitalized era. Despite their critical role, data centers are notable for their significant carbon footprint, attributed to their extensive energy use. It is projected that by 2030, the data center sector will be responsible for 8% of the world's carbon emissions. Nevertheless, the impact of these emissions can be mitigated through the implementation of carbon neutrality strategies within the industrial sector (Cao et al., 2022).

The escalating energy demands of cloud data centers, which serve as a crucial infrastructure for the global digital economy, are causing a surge in carbon emissions. This is raising concerns worldwide among governments and cloud service providers. Data centers, which are significant consumers of electricity, account for 1.8% of the United States' electricity consumption (O'Shaughnessy, 2018). This figure is projected to rise to 20% globally by 2025, according to estimates (Andrae & Edler, 2015). Given that electricity is predominantly generated from carbon-intensive fossil fuels like natural gas and coal, this high level of electricity consumption will lead to substantial carbon emissions. The data center industry is currently responsible for 0.3% of global carbon emissions, a trend that is expected to persist over the next decade (Jones, 2018). As excessive carbon emissions contribute to climate change - one of the most severe challenges facing humanity - data centers pose a significant obstacle to global efforts to mitigate climate change.

Worldwide efforts are underway to reduce the environmental footprint of data centers. In the wake of the European Green Deal, major cloud infrastructure providers and data center operators in Europe have come together to form the Climate Neutral Data Center Pact (Cao et al., 2022). In an unprecedented initiative, 25 companies and 17 associations have pledged to a self-regulatory effort aimed at attaining climate neutrality in European data centers by the year 2030. This commitment encompasses a set of ambitious and quantifiable objectives, including the procurement of carbon-neutral energy, conservation of water, reuse and repair of servers, and recycling of heat. Similarly, the Chinese government has outlined its own goals for reaching a carbon peak and achieving carbon neutrality (Nogrady, 2021). Tencent is accelerating its efforts towards carbon neutrality, with a strategy to eliminate carbon emissions entirely by leveraging cutting-edge Artificial Intelligence (AI) technologies. Similarly, Chindata Group, a prominent provider of carrier-neutral hyperscale data center solutions in China, has announced its ambition to attain carbon neutrality across all its future hyperscale data centers in China by 2030, utilizing entirely renewable energy sources. In the United States, major data center operators are implementing even more aggressive environmental strategies. Google has made a pledge to supply all its global data centers and corporate offices with 100% carbon-free energy by 2030. Microsoft is taking its environmental commitments further by promising to achieve carbon negativity by 2030 and to offset all its historical carbon emissions by 2050.For waste heat reuse of data centers, (Antal et al., 2019; P. C. Huang Benedetta; Zhang, Xingxing; Shen, Jingchun; Löfgren, Isabelle; Rönnelid, Mats; Fahlen, Jan; Andersson, Dan; Svanfeldt, Mikael, 2020) they studied about optimal operation in data centers, workload redistribution and waste reuse of data centers for providing critical services to Urban energy systems (UESs).

The carbon market has been introduced as a policy tool to efficiently offset the carbon emissions from data centers. In terms of technology, it is suggested that in order to achieve carbon-neutral data centers, renewable energy penetration should be increased in tandem with energy efficiency improvements and energy circulation should be boosted. According to reports in 2016, the world's data centers consumed 416.2 terawatt hours of electricity, which was significantly more than Britain's consumption of 300 terawatt hours. Data centers have the same carbon footprint as the aviation sector, making up 3% of the world's electricity supply and roughly 2% of all greenhouse gas emissions. Data centers are expected to consume up to a fifth of the world's electricity and contribute 3.2 percent of global carbon emissions by 2025, according to recent projections. The world's emissions from digital data storage are predicted to reach 14% by 2040, roughly equal to what the US produces currently.(Monserrate, 2022).

The United States Environmental Protection Agency (EPA) (Cao et al., 2022) defines three scopes of carbon emissions for a business entity, as illustrated in Figure 4:

- SCOPE1 Emission includes the direct emission from burning fossil fuels, using company vehicles and other activities that release greenhouse gases, such as operating diesel generators.
- SCOPE2 Emission accounts for the indirect emission from purchasing electricity, heat, or steam from local utilities. There are two ways to measure SCOPE2 Emission: location-based and market-based. The location-based method uses the average carbon emission and electricity production data within a geographical boundary over a certain time period. It reflects the degree of decarbonization of the local grid. The market-based method considers the carbon emission associated with the specific electricity or heat supplier. Different suppliers may have different carbon emission factors that vary from the regional average.
- SCOPE3 Emission encompasses other indirect emissions that are not covered by SCOPE2 Emission, such as the electricity transmission and distribution loss that are not included in SCOPE2 Emission.

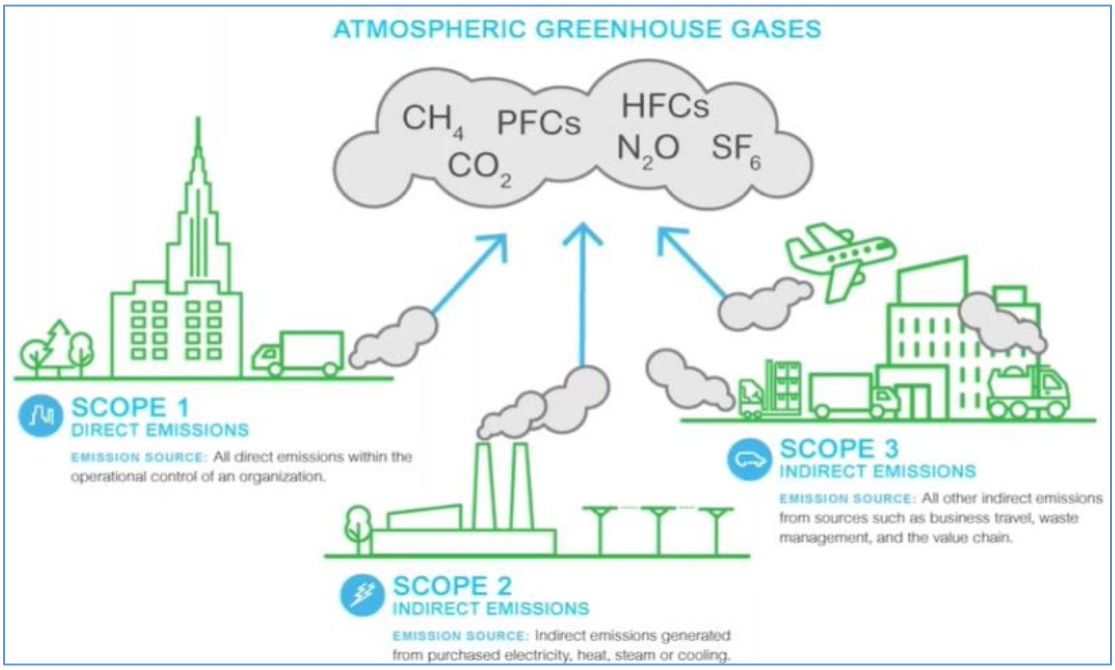

Figure 4. Carbon emissions (Lin & Bunger, 2024)

1.1.6 Why DC power has become interesting?

DC power is a type of electrical power that flows continuously in one direction and is produced by sources like batteries, solar cells, and fuel cells. DC power has become more interesting in recent years due to its advantages over AC power in various applications such as data centers, telecommunication systems, electric vehicles, and renewable energy sources. This thesis aims to explore the factors contributing to the increasing popularity and significance of DC power in contemporary society (Hoey, 2023; Rasheed et al., 2019).

One of the advantages of DC electricity over AC power is its high efficiency. DC power does not waste energy as heat, which makes it suitable for high-power applications that require low energy losses and high performance. According to a study by the Lawrence Berkeley National Laboratory, data centers that use DC power can reduce their cooling costs and energy consumption by up to 30% compared to those that use AC power (Lanzisera, 2010). Similarly, electric vehicles that use DC power can benefit from faster charging times, longer driving ranges, and longer battery life than those that use AC power.

DC electricity offers the benefit of being dependable and consistent. DC power supplies consistent and predictable voltages, making it crucial for delicate equipment like microprocessors and machine drives. DC power decreases the likelihood of power outages and enhances network dependability, particularly in telecommunication systems that necessitate continuous power provision. Moreover, direct current (DC) may be conveniently stored in batteries or capacitors for subsequent utilization, rendering it well-suited for off-grid systems that depend on sustainable energy sources like solar panels and wind turbines.

Another benefit of DC power is its ability to be easily adjusted in size and its ability to work well with other systems. Converters or inverters may readily modify DC power to suit the precise requirements of various applications. DC electricity can be incorporated into current AC power systems or devices through the utilization of rectifiers or transformers. This facilitates a seamless conversion from alternating current (AC) to direct current (DC) electricity without necessitating significant alterations or financial commitments.

1.1.7 Role of Sector Coupling in Data Centers

Sector coupling is the connection of different energy sectors like electricity, heat and transportation in order to increase energy efficiency, reduction in carbon emissions and to increase the flexibility between the systems. Sector can be in variety of combinations such as power to gas, power to heat and heat to power. In data center scenario, Data center is the middle part and it has a sector coupling with the grid and district heating. EU 2030 Climate and Energy Framework has defined climate goals to control global warming to a maximum of 2 degrees and reducing greenhouse emissions requires to use renewable energy sources instead of fossil fuels (Ramsebner et al., 2021).

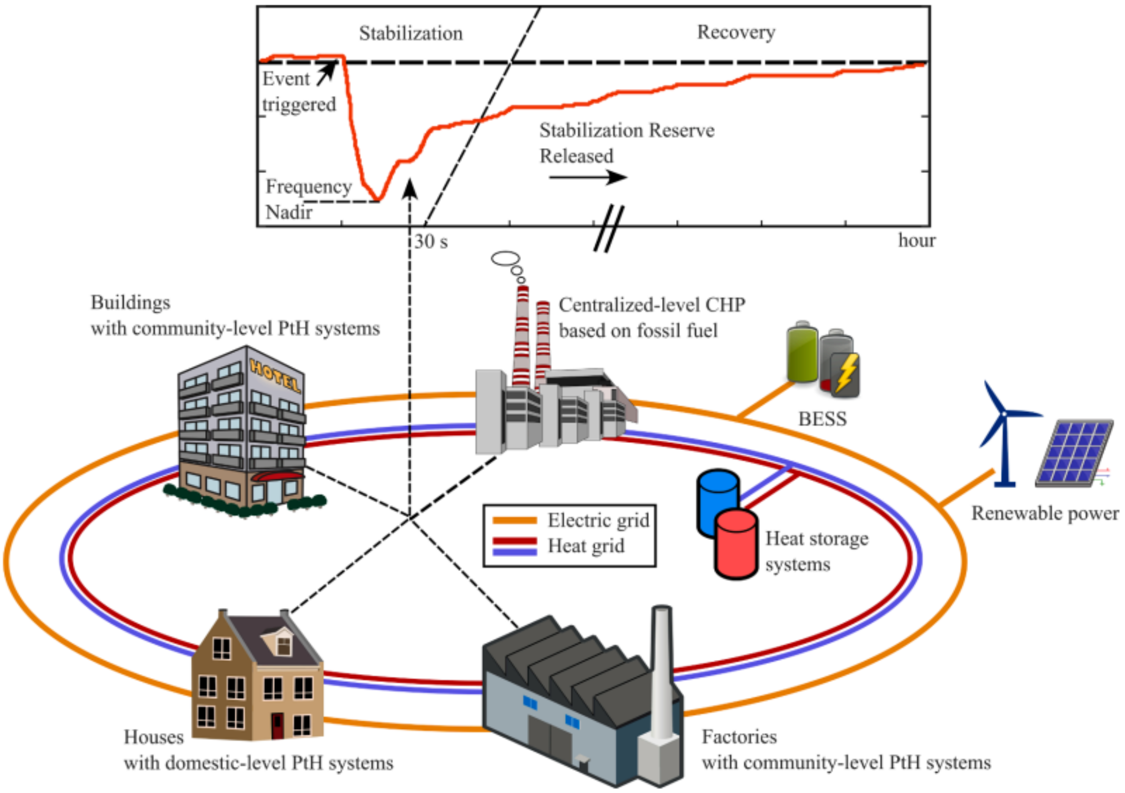

Figure 5. Graphic illustration of the electric-thermal sector coupled frequency control (R. Song et al., 2023)

From the beginning of the 20th century, different sectors of industries, they integrate with each other such as, first battery Electric vehicle (BEV) was displayed in 1892. Basically, sector coupling is the integration of multiple energy sources together to support in terms of to get more flexibility, efficiency and emissions reductions. By the help of sector coupling, energy sectors can become more resilient and flexible.

The sectors can be power, heat and mobility (Ausfelder et al., 2017). The purpose of sector coupling of different energy sectors is to reduce greenhouse gas emissions, utilize waste heat production, to get stability in power grid, stable frequency variations and to minimize usage of fossil fuels. According to Song et al., (2023), integration of power and heat can help to stabilize frequency in power grid because thermal components are affordable, flexible and they have high inertia to store energy and bear fluctuations in power system.

Energy Sector Integration (ESI) refers to a holistic approach that synchronizes the generation, transmission, conversion, and consumption of energy across various sectors, pathways, and timelines. Unlike traditional energy systems that operate sectors independently, ESI offers four primary benefits (Chair, 2021):

- It supports a greater incorporation of renewable energy by leveraging the adaptability provided by energy conversion and storage systems.
- It boosts the overall system's efficiency through the layered utilization of energy, including renewables.
- It facilitates the strategic distribution of both centralized and decentralized energy resources at a systemic level, enabled by market interactions.
- It improves the reliability and robustness of the energy supply by integrating diverse energy infrastructures to complement each other.

The rising focus on carbon-neutral power systems, primarily powered by renewable energy sources, stems from growing concerns over greenhouse gas emissions, energy scarcities, and global warming. Sector coupling, an approach that links different energy domains through the integration of production, consumption, conversion, and storage, holds the potential to address the specific demands of each energy sector. This strategy could minimize the production of excess energy and prevent unnecessary carbon emissions, thereby transforming the conventional power system into a carbon-neutral entity and enhancing the acceptance and utilization of renewable energy. (Son et al., 2023).

Sector Coupling in Facilitating Integration of Variable Renewable Energy in Cities highlights the importance of sector coupling as a key source of flexibility that cities can explore to stabilize power grid operations when integrating high shares of variable renewable energy sources. It presents a range of sector coupling opportunities available for use in cities. The focus is on four main areas: self-consumption of variable renewable energy sources at various scales, the role of thermal energy storage in sector coupling strategies, electro-mobility (a promising scenario for decarbonizing the transport sector with renewable electricity), and green hydrogen (Fridgen et al., 2020).

1.2 Objectives

The rapid development of data centers requires reliable and energy-efficient power solutions. These solutions depend on the power distribution architectures, energy efficiency, and reliability of DC. This thesis explores the advantages and challenges of AC/DC conversion in data center applications

Data centers are the foundation for digital economy, which house a wide range of applications, including social media and scientific research. Nevertheless, they consume a significant amount of energy, resulting in increased operational costs and environmental concerns. The power distribution architecture choices between AC and DC has a considerable impact on the overall energy efficiency and dependability of these data centers. AC power distribution has been extensively employed due to its ease of generation and efficient transmission across great distances. However, most modern electronic devices, including servers and storage units, operate with direct current (DC) power. Multiple conversions between alternating current (AC) and direct current (DC) are required, leading to reduced efficiency and energy dissipation.

DC power distribution, on the other hand, may be able to lower these conversion losses and increase energy efficiency. Furthermore, since energy storage systems and renewable energy sources are mostly DC based, DC systems may be more compatible with them. This has the potential to further improve data center’s resilience. DC power distribution adoption in data centers is not without difficulties, though. Compared to AC systems, these include the need for new standards, safety concerns, and a lack of experience and mature technology.

Thus, a thorough investigation into the architectures of AC and DC power distribution, their effects on energy efficiency and reliability, and possible ways to get around related problems can yield important information for the planning and management of data centers in the future. This serves as the main inspiration behind this thesis.

1.3 Research Questions

- What are the relative benefits and drawbacks of data center power distribution using AC versus DC?
- How do AC and DC power distribution systems contribute to the energy efficiency and reliability of data centers, and what metrics can be employed to assess their performance in these areas?
- How can the use of DC in data centers be defended against the conventional AC power distribution?

1.4 Scope of the Thesis

This thesis aims to explore the alternating current (AC) and direct current (DC) power distribution architectures utilized within data centers, assessing their respective performances, reliability, efficiency, and associated costs. Comprising four chapters, the document initiates with an introductory overview of data centers. It then progresses to a literature review, analyzing various components of data centers. The subsequent chapter delves into the materials and methods, focusing specifically on the diverse power distribution architectures present in data centers. The concluding chapter engages in a comparative analysis of the power distribution architectures.

Moreover, the research incorporates a case study of an actual data center that has adopted a DC power distribution system, examining both its advantages and challenges. The findings aim to offer actionable recommendations for data center operators and designers contemplating a transition to DC power distribution or seeking enhancements to their current AC power distribution frameworks.

2 Literature Review

2.1 Classification of Data Centers

Data center tiers are a system developed by the Uptime Institute to provide a consistent method of comparing typically mission-critical systems infrastructure performance, reliability and resiliency. The tier classification system provides the data center industry with a consistent method of comparing typically mission-critical infrastructure from site to site. The tier system comprises four levels (Tier I to Tier IV) in Table 1, with Tier IV being the most robust. The tier assigned to a data center indicates its level of fault tolerance, or its ability to maintain functionality during various kinds of failures.

Tier I is the simplest infrastructure, while Tier IV is the most complex and has the highest level of fault tolerance. Tier I data centers have non-redundant capacity components and a single, non-redundant distribution path. Tier II data centers include redundant capacity components. Tier III includes concurrently maintainable site infrastructure, and Tier IV adds the concept of fault tolerance to the site infrastructure.

2.1.1 Classification in terms of Tiers

The tier classification influences the design process of data centers by providing guidelines for infrastructure redundancy and fault tolerance. This ensures that the data center will be capable of meeting the business needs of the organization.

The tier system also influences the operational sustainability of the data center. It provides a benchmark for the performance capability of the data center infrastructure, which can be used to identify areas for improvement. More specifically in Table 1., the 'N' method is the minimum capacity for the data center to work normally. It has no backup capacity for equipment failure, so it has no redundancy.

Table 1. Data Center Tiers (T. Chen et al., 2016)

Tier	Structure	Range	Reliability
Tier I	• Single path for IT equipment • Utilized by small businesses • Annual downtime 28.8 hours	Low	99.671%
Tier II	• Some redundancy in power and cooling • Utilized by medium businesses • Annual downtime 22 hours	Medium	99.741%
Tier III	• N+1 fault tolerant • Dual powered IT equipment • Concurrent maintainability • Utilized by larger businesses	High	99.982%
Tier IV	• Fault-tolerant • 2N+ I fully redundant infrastructure • Annual downtime 0.8 hours • Utilized by Enterprise corporations	Very high	99.995%

N+1 or N+X redundancy means that there is one or more extra components (such as UPS, HVAC, or generator systems) besides the necessary components. The '+' sign means that there are backup components ready to take over if a primary component fails. Power goes from the utility, through the UPS/PDU, and connects to the server.

The 2N+1 redundancy method is a combination of 2N and N+1. It doubles the necessary capacity (2N), and adds an extra backup component to each element of the N architecture. It is very resilient and can handle multiple component failures. Even when the primary system is offline, N+1 redundancy is maintained (Zhang, 2023).

2.1.2 Classification in terms of Size

In Table 2, there are different types of data centers that vary in size, location, power demand and purpose. Hyperscale data centers are the largest and most powerful, used by cloud providers. Colocation data centers are smaller and rented by businesses. Enterprise data centers are owned and operated by companies on-premises. Edge data centers are located near to end users for low latency and high performance. Modular data centers are self-contained and scalable units that can be placed anywhere.

Table 2. Data Center Types (T. Chen et al., 2016; Rashid, 2019)

Type	**Location**	**Power Demand**	**Applications**
Hyperscale	Off-premises	50MW-300 MW	Support the massive computing and storage needs of cloud providers
Colocation	Off-premises	<50MW	Renting Data Center services
Enterprise	On-premises	<2MW	Owned by companies for their own IT infrastructure
Edge	Located near to end users	100KW - 1MW	Reduce latency and improve performance for as real-time analytics, IoT devices, etc
Modular	Both On and Off-premises	10KW – 100KW	Easy to scale up or down

2.2 Data center and Future Power grids

Data centers can benefit from actively engaging with the new power system, as they have various ways to cope with power grid fluctuations and generate profits (Guo et al., 2021). The Figure 6 shows the different types of resources that DCs can use within their premises, such as batteries, UPS, generators, renewable energy systems, and Feul cells (Y. Chen et al., 2023). These resources are essential for supporting demand-side response activities effectively, as they can transfer electricity in time and space to relieve grid congestion, and perform peak shaving and valley filling operations within data centers and regional power grids. When the power grid is under stress or needs to reduce electricity consumption due to environmental or system constraints, data centers can dynamically adjust their computing workloads to save power without affecting critical tasks (Almalaq et al., 2022). This enables better integration of renewable energy and conventional power generation systems, maximizing the use of clean energy sources while accounting for their variability due to weather conditions and other factors beyond control. Large and flexible energy loads are valuable demand response resources for maintaining grid stability. For example, in 2011, many DCs in the US participated in urgent DR initiatives, avoiding potential financial losses of millions of dollars (Errapotu et al., 2020).

In terms of supporting the power grid, data centers have the potential to contribute significantly. Google, for instance, has developed a new approach for demand response across its data centers. This approach allows Google to temporarily reduce the power demand of a data center when called on to do so by an external power system partner, such as a utility or grid operator. This is done by shifting non-urgent compute tasks to other times and locations, without impacting the performance of Google services. This not only helps reduce the data centers electricity consumption during high stress on the local power grid but also provides valuable flexibility to help local grids continue operating reliably and efficiently (Mehra & Hasegawa, 2023). Microsoft has deployed hydrogen fuel cells at one of its data centers to power its backup generators and also to participate in the California Independent System Operator's market for frequency regulation (Roach & Microsoft, 2022).

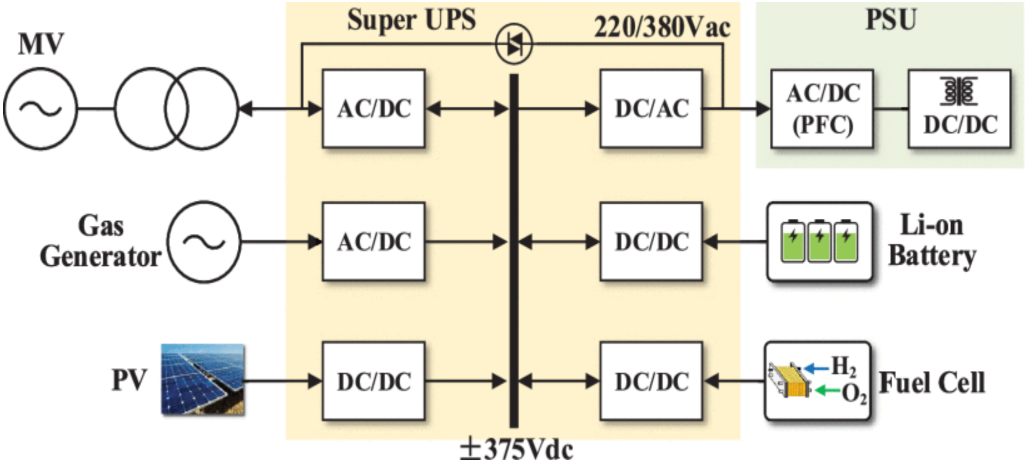

Figure 6. Data Center and Distributed Power Generations(Y. Chen et al., 2023)

Moreover, data centers can optimize their integration with the electrical, thermal, and IT networks to meet sustainability objectives and gain primary energy savings. Innovative scenarios are being explored for exploiting the data centers electrical, thermal, and workload flexibility as a commodity. The potential of combining IT load migration with the availability of renewable energy sources (RES) to increase the amount of energy flexibility is also being investigated.(Cioara et al., 2020) (Tudor Cioara et al).

In the context of energy transition, the rapid adoption of new technologies such as electric cars and heat pumps means electricity is expanding into realms previously dominated by fossil fuels, increasing the demands on grids. Grids are essential to decarbonize electricity supply and effectively integrate renewables (Roozbehani et al., 2012). Variable Renewable Energy (VRE) like solar photovoltaics and wind have characteristics that require specific measures to integrate these technologies into current power systems (ESMAP, 2019).

According to Monteiro et al., (2021), data centers can influence future power grids is by adopting new architectures and technologies that can enhance their energy efficiency and power quality. Data centers can adopt hybrid AC/DC grids that can reduce the conversion losses and harmonics associated with AC/DC power conversion devices. Data centers can also use solid-state transformers (SSTs) that can enable bidirectional power flow, fast switching, and high-frequency isolation between the grid and the data center loads. Furthermore, data centers can employ unified multi-port systems that can integrate various technologies, such as renewable energy sources, energy storage systems, or electric vehicles, into a single interface with the grid.

The study by Power, (2021) examines the potential benefits of utilizing data center load distribution proactively for electric power load balancing within the power grid. This investigation is framed as a two-stage problem: initially, the power grid operator endeavors to balance the electric power load, followed by data centers striving to minimize their aggregate energy costs in the subsequent stage. Simulation outcomes reveal that the suggested approach enhances load balancing efficiency by approximately 12%, as measured by the electric load index, and concurrently reduces the energy expenses of data centers by an average of 46%.

2.3 Data Center Parts

2.3.1 Uninterruptible Power Supply (UPS)

Uninterruptible Power Supply (UPS) is a device or system that provides continuous and stable electric power to critical equipment in data centers, such as IT servers, network devices, and cooling systems. UPS systems prevent data loss, downtime, and damage caused by power outages, fluctuations, or disturbances. UPS systems also serve as a bridge between the utility power and the backup generators, which may take some time to start and stabilize (Eaton, n.d.-b; Jose, 2021; Worton, 2021).

There are three main types of UPS systems used in data centers: standby, line-interactive, and online double-conversion. Each type has different characteristics, advantages, and disadvantages, depending on the power quality, availability, and efficiency requirements of the data center.

Standby UPS systems are the simplest and most economical type of UPS, as illustrated in Figure 7. They operate in standby mode, meaning that they only switch to battery power when the utility power fails or falls outside a predefined range. The switching time is typically 2 to 10 milliseconds, which may cause some sensitive equipment to malfunction or shut down. Standby UPS systems are suitable for low-power and low-priority applications that can tolerate brief interruptions and moderate power quality.

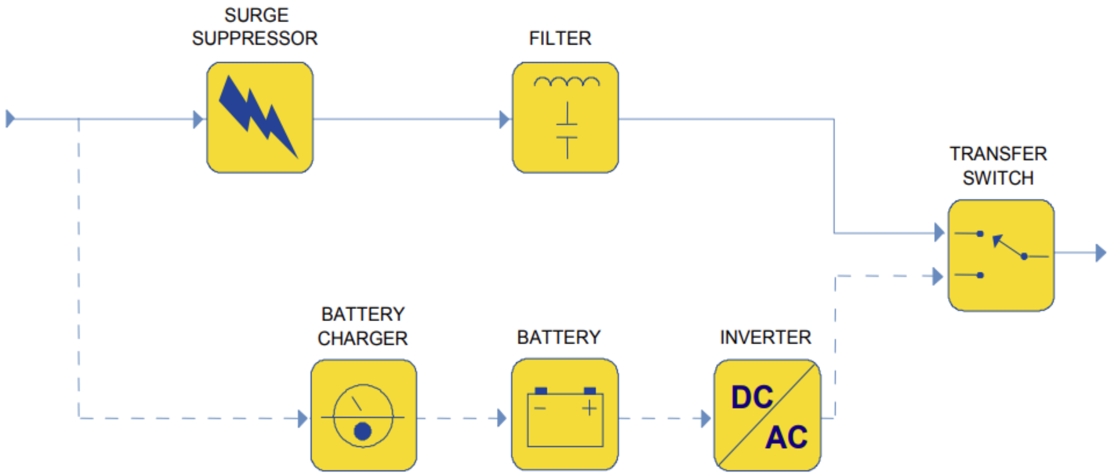

Figure 7. StandBy UPS(Rasmussen, n.d.)

Line-interactive UPS systems, as illustrated in Figure 8 are similar to standby UPS systems, but they have an additional feature: a voltage regulator. The voltage regulator can adjust the output voltage to compensate for minor fluctuations in the utility power, such as brownouts or surges. This reduces the need to switch to battery power and extends the battery life. Line-interactive UPS systems have a switching time of 2 to 4 milliseconds, which is faster than standby UPS systems but still not ideal for highly sensitive equipment. Line-interactive UPS systems are suitable for medium-power and medium-priority applications that require moderate power quality and availability.

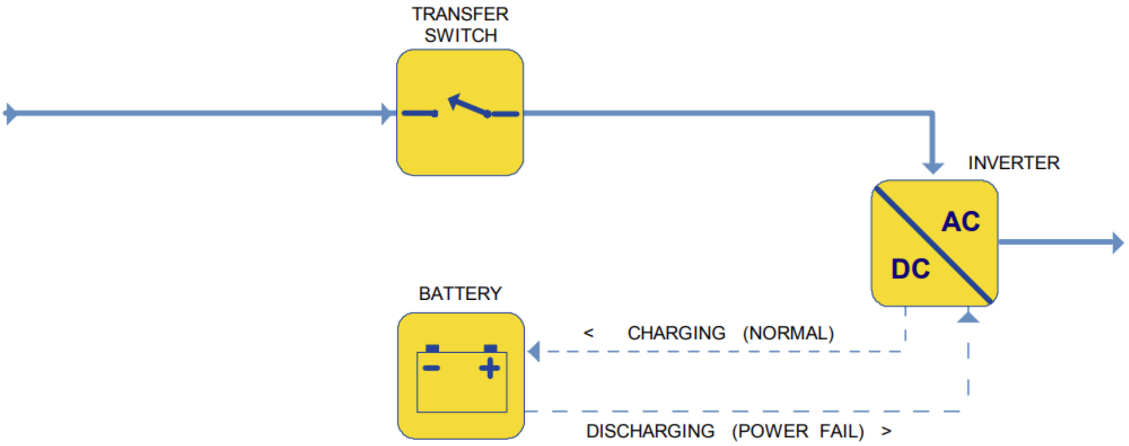

Figure 8. Line interactive UPS(Rasmussen, n.d.)

Online double-conversion UPS systems, as illustrated in Figure 9 are the most advanced and reliable type of UPS. They operate in online mode, meaning that they continuously convert the utility power from AC to DC and then back to AC. This process eliminates any power disturbances and provides a clean and consistent output voltage and frequency. Online double-conversion UPS systems have no switching time, which means that they can protect the most sensitive and critical equipment from any power anomaly. Online double-conversion UPS systems are suitable for high-power and high-priority applications that require high power quality and availability. The Table 3 is about the different type of UPS standards and its properties.

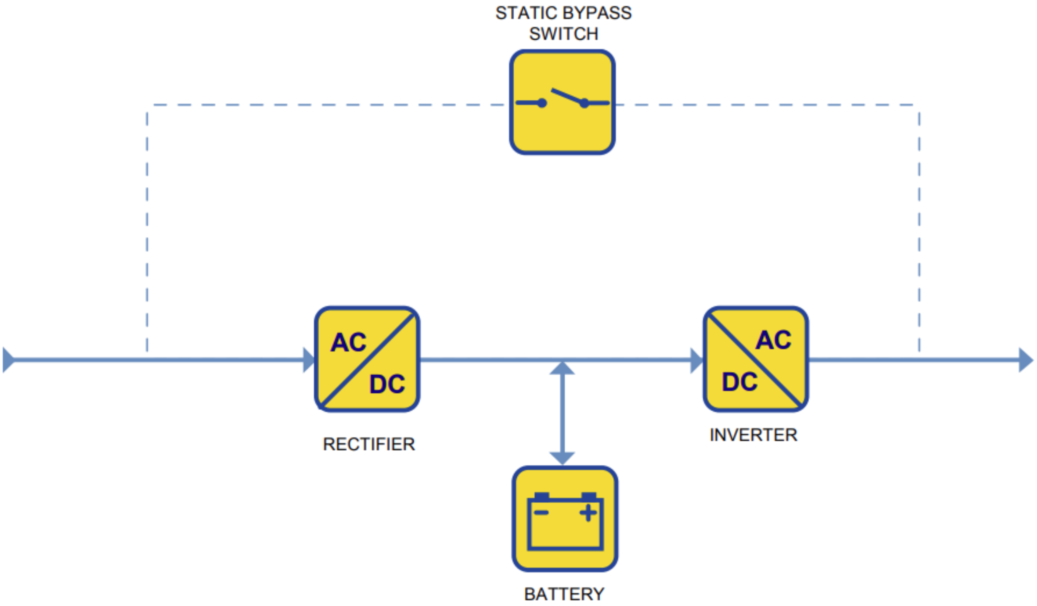

Figure 9. Online Double Conversion UPS(Rasmussen, n.d.)

Table 3. Different UPS topologies.(Worton, 2021)

Feature	**Offline**	**Line-interactive**	**Online**
Size	Compact	large & heavy	small & light
Practical Power Range (kVA)	0-0.5	0.5-5	5-5000
Voltage Conditioning	Low	Design Dependent	High
Cost per VA	Low	Medium	Medium
Efficiency	High (typically 95-98%)	High (typically 90-96%)	Low-Medium (typically 80-90%)
Cost	Small	Medium	High
Applications	Offices	Medium businesses	Telecoms; Communications

2.3.2 Battery Technologies

Batteries play a crucial role in data centers, particularly in the context of Uninterruptible Power Supply (UPS) systems. They serve as a short-term power source, providing a very short ride-through time until engine generators or some other onsite power production system can take over. There are different types of batteries that can be used for data center applications, such as lead-acid, lithium-ion, and sodium-ion. Each type has its own advantages and disadvantages in terms of performance, cost, safety, and environmental impact. The Table 4 is about different type of energy storage systems and their technical specifications which can be used with respect to power system needs.

Lead-acid batteries are the most widely used technology for data centers, due to their proven reliability, low cost, and high recyclability. However, they also have some drawbacks, such as low energy density, heavy weight, limited cycle life, and maintenance requirements. These batteries are non-combustible and have a water-based electrolyte, which reduces the fire risk compared to lithium-ion batteries (Ashton & Flores, 2022).

Lithium-ion batteries are emerging as an alternative technology for data centers, due to their higher energy density, longer cycle life, and lower maintenance needs. They also offer benefits such as less floor space, reduced system weight, and higher efficiency. However, lithium-ion batteries are more expensive than lead-acid batteries and have a flammable electrolyte, which poses a fire hazard and requires more stringent safety standards and regulations. Lithium-ion batteries also have lower recyclability and higher environmental impact than lead-acid batteries(Avelar & Zacho, 2016; He et al., 2022; Lawrence, 2020).

Sodium-ion batteries are another promising technology for data centers, as they have similar performance characteristics to lithium-ion batteries but use abundant and low-cost sodium instead of scarce and expensive lithium. Sodium-ion batteries also have a non-flammable electrolyte and a high thermal stability, which enhances their safety and durability. However, sodium-ion batteries are still in the early stages of development and have not been widely deployed in data center applications yet. They also face challenges such as low voltage, high self-discharge rate, and limited cycle life (Haider et al., 2020).

Table 4. Properties for energy storage systems (ESS)(Akinyele & Rayudu, 2014; H. Chen et al., 2009; Krishan & Suhag, 2019; May et al., 2018; Nadeem et al., 2019)

ESS	Power range (MW)	Discharge time	Power density (Wh/kg)	Energy density (Wh/kg)	Efficiency (%)	Lifetime (years)	Cycling capacity	Cost, $/KWh
SHS	250	-	-	-	50-90	10-30	>5,000	-
LHES	5	-	-	-	75-90	10-30	-	-
PHES	10-5,000	1-24 h	-	0.5-1.5	70-85	30-60	12×10^3–30×10^3	250–350
GES	40-1,600	1-4 h	-	-	75-80	-	-	-
CAES	3-300	1-24 h	-	30-60	40-80	20-50	0.5×10^3–13×10^3	200–250
FES	0.1-20	Sec-min	400-500	5-80	70-95	15-20	20×10^3–100×10^3	-
Hydrogen	0.1-50	Secs-24 h	5-800	600-1,200	20-66	10-20	20×10^3	-
Lead-acid	0-20	Secs-hours	75-300	30-75	70-90	5-15	200-2,000	400–600
Nickel-Cd	0-40	Secs-hours	150-300	40-90	60-90	10-20	3,000-4,000	1200–1500
Sodium sulphur	0.05-8	Secs-hours	90-230	150-240	75-90	10-15	2,000-4,000	600–800
Li-ion	0-0.1	Mins-hours	360	100-200	70-85	5-15	1,000-10^4	1250–1500
VRB	<3	<10 h	75-150	35-60	70-85	10	$>16\times10^3$	750–850
PSB	<15	<20 h	-	15-30	60-75	-	15×10^3–20×10^3	-
Zn-Br	-	Secs-10 h	90-110	75-85	65-75	5-10	$>12\times10^3$	600–800
Capacitor	0-0.05	Millisecs-1 h	$=10^5$	5	0.05-5	60-90	5	-
Supercapacitor	0-0.3	Millisecs-1 h	500-5,000	1.5-2.5	75-95	>20	$>10^5$	-
SMES	1-10	Millisecs-8 s	500-2,000	0.5-5	>95	>20	$>10^5$	-

2.3.3 Power distribution unit (PDU)

Power distribution units (PDUs) are devices that distribute electric power to the equipment in a data center or networking center. They are essential for ensuring reliable and efficient power delivery to the servers, switches, routers and other devices that process and store data. PDUs can also perform power monitoring, load balancing, remote control and environmental sensing functions. Data centers can utilize many types of Power Distribution Units (PDUs) based on the facility's size, complexity, and power demands. Several prevalent types of Power Distribution Units (PDUs) include (Strieter, 2023):

Basic PDUs: These are uncomplicated power strips equipped with surge protection that supply power to the equipment housed in a rack or cabinet. They lack network connectivity and intelligent capabilities. These are appropriate for tiny server rooms or data centers with low power density and in close proximity to the IT workers.

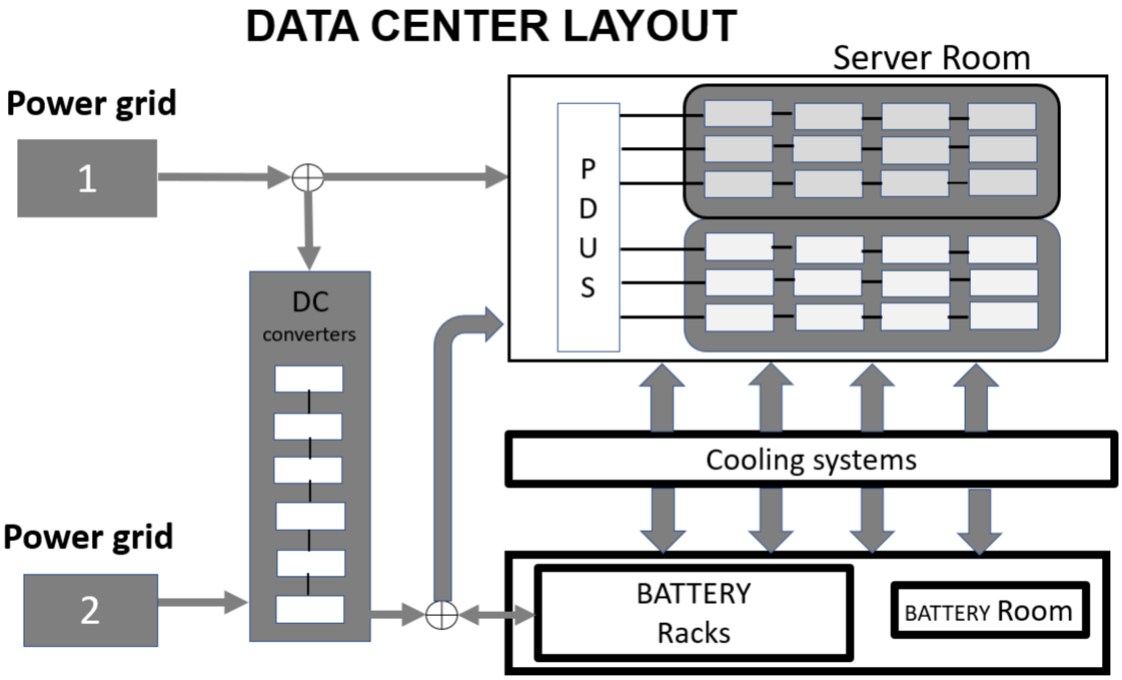

Figure 10. Data Center and Power Distribution Unit.(Haider et al., 2020)

Metered PDUs: Metered PDUs are power distribution units that have the capability to monitor and show the amount of power being consumed by the equipment that is connected to them. They can assist the IT personnel in monitoring power consumption, optimizing load allocation, and preventing circuit overload or underutilization. Although they possess network connectivity, they do not permit remote control or the ability to swap the outlets.

Monitored PDUs: Monitored PDUs are power distribution units that have the capability to monitor and provide information on the power consumption. This information can be reported to a remote management system. They can assist the IT personnel in enhancing energy efficiency, resolving problems, and strategizing for future capacity. These devices possess network connectivity and enable remote control or switching of the outlets.

Switched PDUs: Switched PDUs refer to power distribution units that have the capability to remotely activate or deactivate certain outlets or groups of outlets. They can assist the IT personnel with managing the power status of the equipment, executing planned maintenance tasks, restarting or turning off devices, and maximizing energy efficiency. They possess network connectivity and provide all the functionalities of monitored PDUs.

Efficient usage of PDUs:

- Choosing high-quality PDUs with low power losses and high reliability
- Using high-voltage PDUs (such as 208V or 240V) instead of low-voltage PDUs (such as 120V) to reduce the current and resistive losses
- Using three-phase PDUs instead of single-phase PDUs to balance the load and reduce the number of cables and transformers
- Using modular PDUs instead of fixed PDUs to adapt to changing power needs and avoid over provisioning or under provisioning
- Using intelligent PDUs with power monitoring and management features to optimize the power distribution and utilization

Some of the benefits of using efficient PDUs are:

- Reducing energy costs and carbon footprint
- Improving reliability and availability
- Enhancing performance and scalability
- Simplifying maintenance and management

2.3.4 Power Supply Unit (PSU)

Power supply units (PSUs) are essential components of data centers, as they provide the electrical power to the servers and other devices. PSUs need to be efficient, reliable, and scalable to meet the increasing demand for computing power and energy efficiency. One of the key design choices for PSUs is the voltage level of the power distribution system in the rack level from Figure 1. Traditionally, data centers have used 12 V as the standard voltage level, but recently data centers have transitioned their attention from the 12 V to the 48V power architecture, as depicted in Figure 12 and Figure 14, for multiple reasons (Kim, 2016). The 48V power architecture exhibits reduced dissipation loss on the bus due to its utilization of a higher voltage. Additionally, a 48V battery bank is directly linked to the 48V bus in order to provide power to the loads in case of an energy shortage. This setup eliminates the need for an additional UPS in the 12V system, hence preventing any unnecessary power loss. Currently, there is a growing requirement for higher power per server rack, which requires power supply units with both high power and high-power density. The power supply unit must have a minimum power output of 3 kW, along with a high-power density and excellent efficiency. Several 3 kW power supply devices have been introduced, boasting impressive efficiency levels of up to 98% and power density below 50 W/in^3 (Fernandez, 2018).

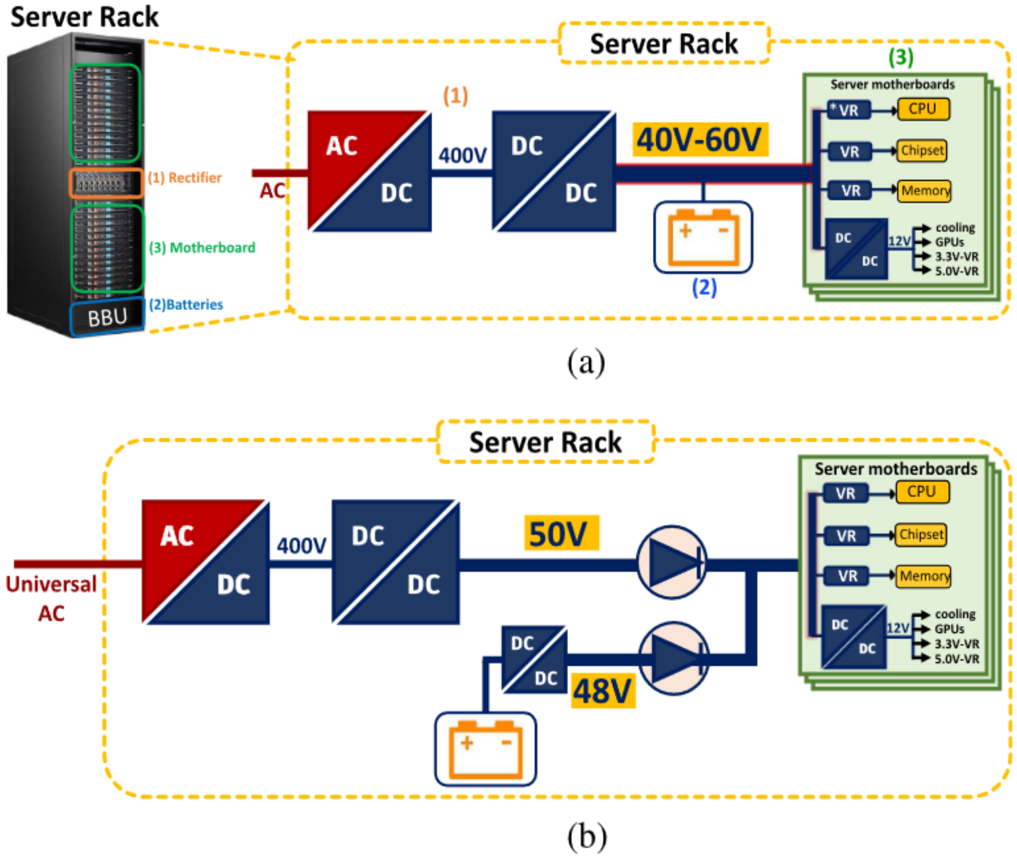

Figure 11. 48-V bus architecture. (a) Wide-range 40–60-V bus—open rack V2 . (b) Narrow-range 48-V bus open rack V3 (Nabih & Li, 2021)

2.3.5 48 VDC Power Supply:

The 48 VDC conversion technique is a recent method aimed at enhancing power density and reducing power losses in power supply units in data centers. The primary idea is to substitute the traditional 12 V power distribution bus with a 48 V bus, and employ high-efficiency converters at the point of load (POL) to transform the 48 V to lower voltage levels. By employing this approach, the resistive losses and the diameters of the cables and connections are reduced, resulting in a fourfold decrease in the current of the distribution bus. In addition, the POL's converters have the ability to utilize smaller passive components and function at higher switching frequencies, resulting in increased power density and reduced cooling needs. Reducing the current and consequently the power losses in the cables and connectors is the primary reason for selecting 48 V as the power distribution voltage. In addition to lowering the size and weight of the cables and connectors, this can increase the power system's overall efficiency and dependability. However, since the majority of loads in data centers require lower voltages, like 1.8 V, 3.3 V, or 5 V, 48 V also presents some difficulties for the PSU design. In order to step down the 48 V to the proper voltage level for each load, a conversion stage is therefore required (Nabih & Li, 2023; OCP, 2016).

To distribute power from 48 V to the POL, a number of architectures are available, including direct single-step conversion and two-step (regulated or unregulated) conversion. In the two-step conversion process, a voltage regulator (VR) converter supplies the final output voltage (e.g., 1.8 V) to the load after an intermediate 12 V rail that is either unregulated or regulated by a DC-DC converter. By using a single DC-DC converter to convert 48 V directly to the output voltage, the direct single-step conversion does away with the intermediary 12 V rail (WIWYNN, 2017).

According to Analog, (2022), switched tank converter (STC) topology is one illustration of a high-efficiency converter for the two-step conversion with an unregulated 12 V rail in Figure 13. The STC is an unregulated, open-loop, 4:1 converter that reaches its maximum efficiency in the 98%–99% range when it is in soft-switching mode. The STC transfers energy from the input to the output in a sinusoidal waveform using a resonant tank circuit made up of an inductor and a capacitor. With minimal ripple and noise, the STC can manage high input voltages of up to 60 V and high output currents of up to 200 A.

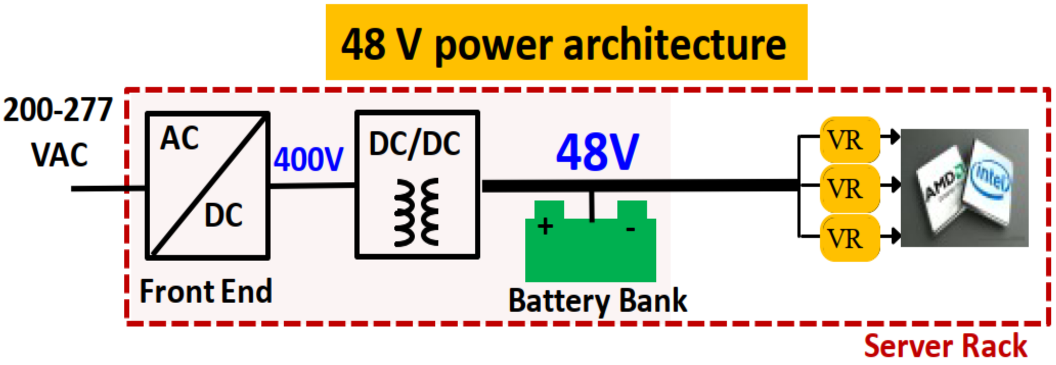

Figure 12. 48v Architecture (Nabih & Li, 2021)

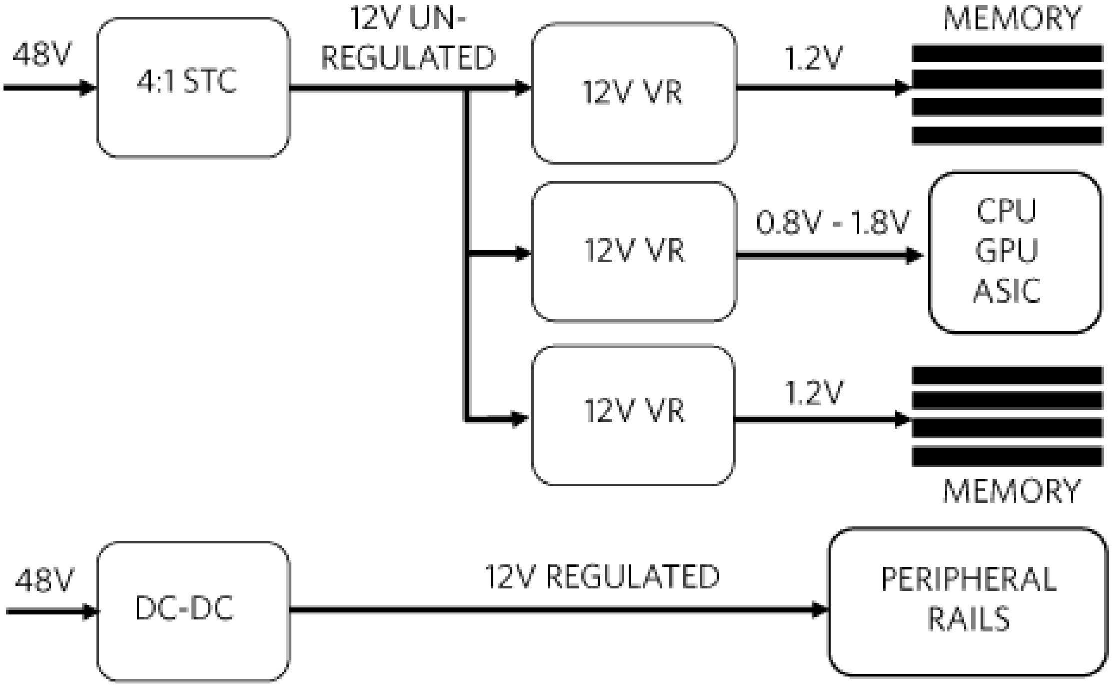

Figure 13. 48v architecture (Analog, 2022)

According to ST, (2022) reports that the overall efficiency of a two-step conversion with an unregulated 12 V rail is approximately 90%, whereas an unregulated 12 V rail has an overall efficiency of approximately 88%. The overall efficiency of the direct single-step conversion is approximately 91%. These figures, however, could change based on the switching frequencies, component choices, load levels, and layout.

Another example of a high-efficiency converter for the direct single-step conversion is the multiphase buck converter topology, proposed by Paultre, (2018). The multiphase buck converter is a single-stage, regulated converter that uses multiple parallel phases to share the load current and reduce the stress on each phase. The multiphase buck converter can achieve up to 96% efficiency at full load and up to 98% efficiency at light load. The multiphase buck converter can also provide fast transient response, low output impedance and high-power density.

2.3.6 12 VDC Power Supply:

12 VDC conversion method is the conventional approach that has been widely used in data center PSUs for decades. The main idea is to use a 12 V power distribution bus that supplies power to various loads in the server rack, such as CPUs, GPUs, memories, HDDs, PCIe devices and fans. Each load has its own VR converter that steps down the 12 V input to the required output voltage (e.g., 1.2 V).

The main advantage of the 12 VDC conversion method is its simplicity and compatibility with existing standards and infrastructure. However, the main disadvantage is its low efficiency and high-power losses. As the power demand from digital chips (CPU, GPU, TPU) is rising, the current in the distribution bus is also increasing, which leads to higher resistive losses and higher temperature rise. Moreover, as the output voltage levels are decreasing (<1V), the VR converters have to operate at very high duty cycles (>90%), which reduces their efficiency and increases their switching losses(Analog, 2022).

According Paultre, (2018), the overall efficiency of the 12 V conversion method is about 85% at full load and about 87% at light load. However, these values may vary depending on the load conditions, switching frequencies, component selection and layout design.

One example of a Voltage regulator converter for the 12 V conversion method is the multiphase buck converter topology, proposed by (Intel, 2018). The multiphase buck converter is a single-stage, regulated converter that uses multiple parallel phases to share the load current and reduce the stress on each phase. The multiphase buck converter can achieve up to 94% efficiency at full load and up to 96% efficiency at light load. The multiphase buck converter can also provide fast transient response, low output impedance and high-power density.

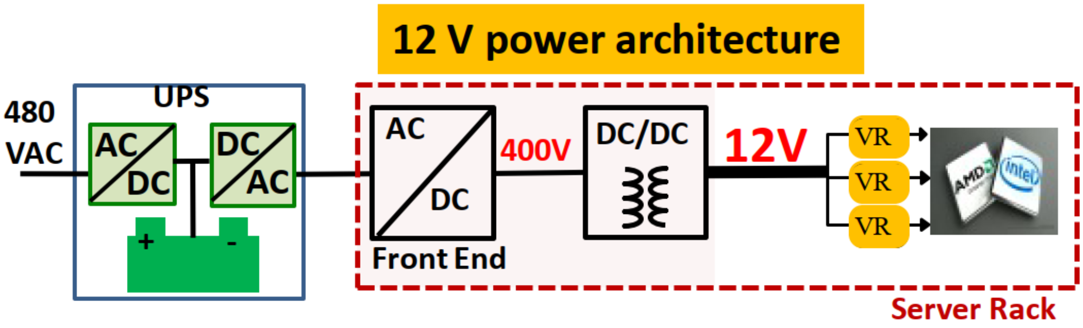

Figure 14. 12v Architecture (Nabih & Li, 2021)

Table 5. PSU Efficiency Comparison(SE, 2024)

Feature (50 kW Load)	**Conventional**	**Rack-level PSU (12VDC)**	**Rack-level PSU (48VDC)**
Efficiency (Load 100%)	77.9%	85.4%	90%
Losses (kW) (%)	14.2kW (28.2%)	8.6kW (17.2%)	5.6kW (11.2%)
Annual Energy Cost (€)	12000	9000	6000

The comparison presented in

Table 5. demonstrates that the largest improvement in architecture efficiency was 13.1 percentage points. This improvement was observed when transitioning from a conventional power supply unit (PSU) architecture to a rack-level PSU architecture utilizing 48v DC. This results in a decrease of losses by 17%. The 12 VDC rack-level power supply unit (PSU) architecture achieved a significant improvement in efficiency, with a gain of 7.3 percentage points compared to the conventional architecture. This translates to a reduction in losses of 11%. Figure 13. displays a considerable disparity in efficiency among three distinct types of power supply units. The 48VDC rack-level power supply unit (PSU) architecture demonstrated a 4.6 percentage point increase in overall efficiency compared to the 12VDC rack-level architecture, resulting in a 6% decrease in losses.

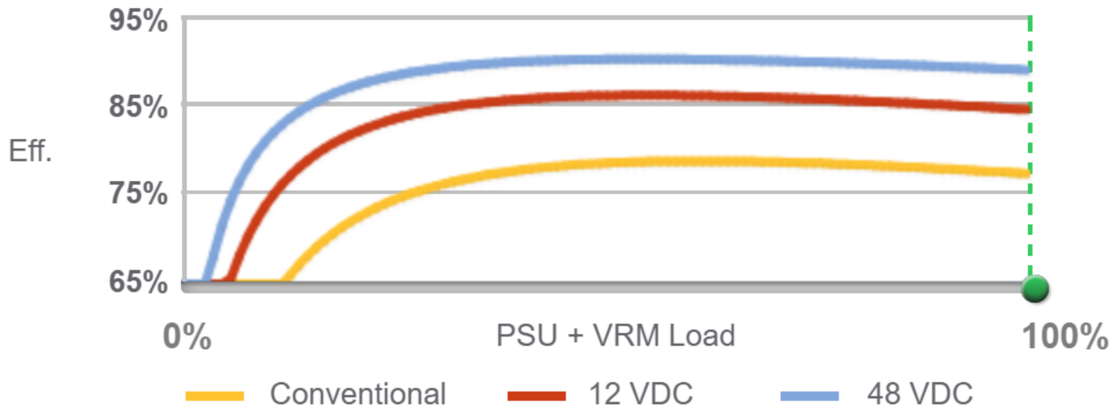

Figure 15. PSU Efficiency Comparison

From

Table 5 and Figure 15, we can see that the 48 VDC conversion method has several advantages over the 12 VDC conversion method, such as higher efficiency, lower power losses, higher power density and lower cooling requirements. However, the 48 V conversion method also has some challenges, such as initial higher cost, higher complexity and lower compatibility with existing infrastructure.

For 12 VDC, which has higher current and hence higher power losses in the cables and connectors. This can degrade the overall efficiency and reliability of the power system, as well as increase the size and weight of the cables and connectors. Moreover, 12 V may not be able to support the increasing power demand from modern processors that require up to 700-800 W of power.

2.4 Energy Efficiency Metrics

Energy metrics play a crucial role in the design and management of data centers. They help data center managers measure and implement cost and power savings. These metrics are pivotal in designing and optimizing energy-efficient operations to curb excessive energy consumption in data centers.

The management of data centers (DCs) primarily focuses on two critical aspects: energy consumption and thermal performance. To effectively monitor and control these variables, various performance metrics have been introduced, which are frequently utilized to evaluate the energy efficiency of data centers. Nevertheless, the extent to which these metrics encourage reduced energy consumption remains largely unexplored (Shao et al., 2022; Whitehead et al., 2014).

A proposed energy efficiency model, based on metrics, aims to classify data centers into distinct measurable units. This model segments a data center into four key areas, applying specific metrics to assess their efficiency and performance. In light of escalating energy costs and policy-driven pressures, energy efficiency has emerged as a pivotal concern in the design of data centers. The growing demand has led to increased power consumption, making electricity the most significant expense in operating a DC. Typically, 80% of a data center's capital costs are attributed to IT power supply and cooling systems, with the construction of the DC accounting for the remaining 20% (Jamalzadeh & Behravan, 2012; Shao et al., 2022).

A breakdown of the energy consumption in the system is presented in Figure 16. Site infrastructures such as the Heating, Ventilation and Air Conditioning (HVAC) systems account for 40% of the total energy input, while IT equipment consumes the remaining 60%. However, only 30% of the energy allocated to IT equipment is utilized for computation, and the rest is dissipated by components such as power supply, fans and drivers of the IT equipment. The right-hand section of Figure 16 shows that the computational performance of IT devices is limited by their low energy efficiency. Table 6 illustrates energy efficiency metrics which are important to check the performance and efficiency of a data center.

The thermal management assumes a key role in achieving energy saving during the operation of a DC and for the improvement of the IT equipment reliability. Servers are less susceptible to failure and faults when operating at certain environmental conditions. Therefore, the effect of the DC thermal performance on metrics is an important aspect to consider.

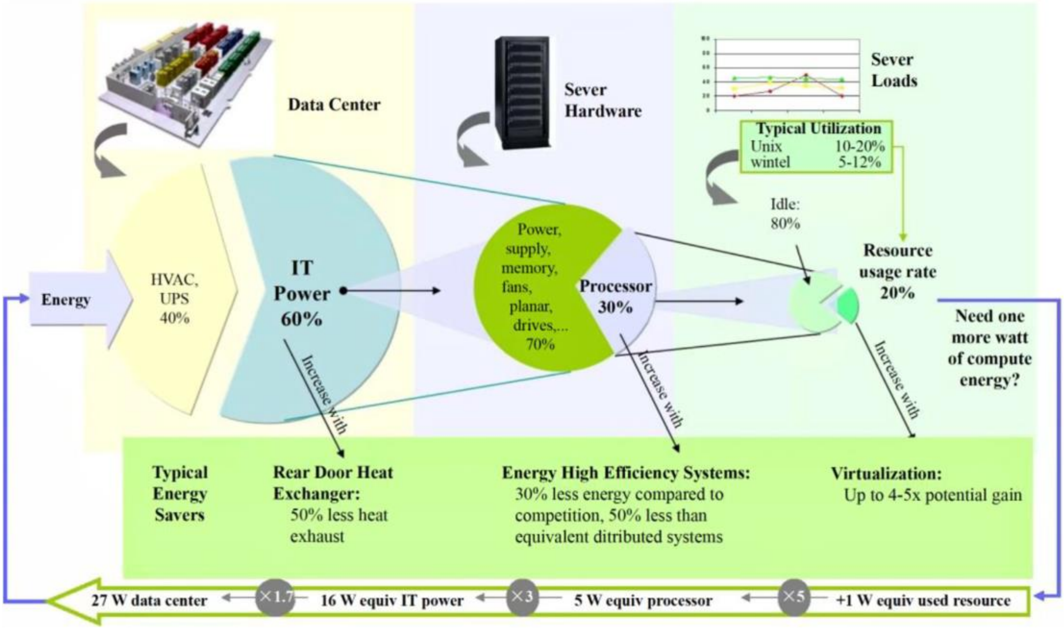

Figure 16. Energy chain in data centers (Shao et al., 2022)

2.4.1 Limitations of energy metrics (PUE)

PUE is a common metric, but it has limitations: 1) It does not account for the weather conditions in different regions where data centers are located, so it is not fair to compare the PUE of data centers in different places. 2) PUE can encourage data centers to reduce the energy consumption of their infrastructure, but it does not measure the energy efficiency of IT equipment, which can lead to inaccurate evaluation of the data center's actual productivity. For example, Whitehead et al., (2014) showed that the PUE value can decrease over time due to the increased power consumption of aging IT equipment, even without any infrastructure improvement. On the other hand, when IT equipment uses technologies like virtualization, it can reduce the number and power consumption of IT devices, which is good for data centers. However, the total energy consumption will not decrease proportionally, because the relationship between the total energy consumption and the IT equipment's energy consumption is not linear (Zoie et al., 2017). 3) PUE does not include the concept of time in its calculation, so it cannot provide a meaningful direction for energy saving for data centers (Yuventi & Mehdizadeh, 2013).

Table 6. Data center energy efficiency evaluation metrics related to power supply

Metrics	Formula	Function	Category	Applicability	Range	Reference
PUE	Total Facility Power Consumption / IT Equipment Power Consumption	Measures the overall energy efficiency of a data center	Energy Conservation	All data centers	1-inf	(Shao et al., 2022)
DCIE	IT Equipment Power Consumption / Total Facility Power Consumption	Measures the efficiency of the data center infrastructure, excluding IT equipment	Energy Conservation	All data centers	0-1	(Shao et al., 2022)
WUE	Total Water Consumption / IT Equipment Power Consumption	Measures the efficiency of water usage in a data center	Eco-Design	All data centers	0- inf	(Patterson et al., 2011)
CUE	Total Carbon Emissions / IT Equipment Power Consumption	Measures the carbon emissions associated with a data center's energy consumption	Eco-Design	All data centers	0- inf	(Azevedo et al., 2010)
ITEE	IT Equipment Power Consumption / IT Equipment Performance	Measures the energy efficiency of IT equipment	Energy Conservation	All IT equipment	0- 5	(Jamalzadeh & Behravan, 2012)
DCeP	Useful Work / Total Facility Enegy	Measures the energy efficiency of data centers	Energy Conservation	All data centers	0-inf	(Shao et al., 2022)
GEC	Green Energy used by Data Center / Total Facility Energy	Total green energy consuption	Eco-Design	All data centers	0-1	(Shao et al., 2022)

2.5 Role of Circuit Breaker in HVDC power systems:

Circuit breakers are devices that can interrupt the flow of electric current in case of a fault, such as a short circuit or an overload. They are essential for the protection and safety of high voltage direct current (HVDC) systems, which are used for transmitting large amounts of power over long distances and interconnecting different power grids. HVDC systems are especially suitable for integrating renewable energy sources, such as offshore wind farms and solar power plants, with the main power grids (Taherzadeh et al., 2023).

One of the main challenges of HVDC systems is the interruption of DC faults, which can cause severe damage to the converters and other components. Unlike AC faults, DC faults do not have natural zero-crossing points, which makes them harder to clear. Moreover, DC faults can generate high fault currents and arc voltages, which can lead to fire hazards and equipment failures (Barnes et al., 2020).

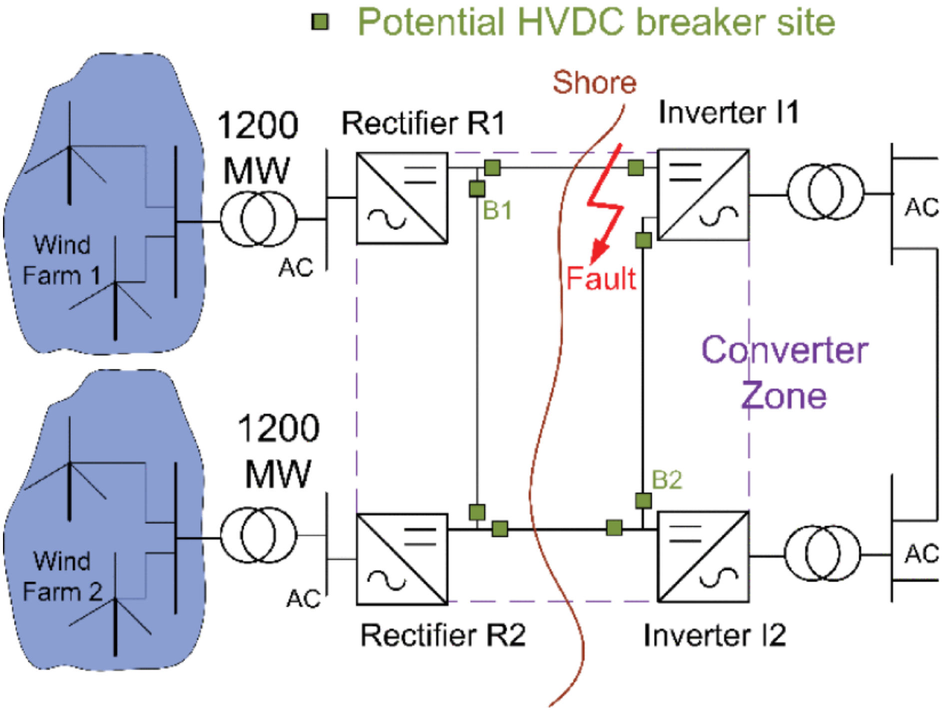

Figure 17. Single-line diagram of HVDC scheme with fault and showing converter blocking, fault and potential DC breaker points.(Taherzadeh et al., 2023)

Therefore, fast and reliable DC circuit breakers (DCCBs) are necessary for the development of large-scale HVDC grids. DCCBs can isolate the faulted section from the rest of the system, limiting the fault current and arc voltage, and restoring the normal operation as soon as possible. DCCBs can also improve the stability and reliability of the HVDC system by preventing cascading failures and blackouts (Loucks, 2013).

There are different types of DCCBs, such as mechanical, hybrid, and solid-state DCCBs. Each type has its own advantages and disadvantages in terms of performance, cost, complexity, and maintenance. Mechanical DCCBs use mechanical switches to interrupt the fault current, but they have slow response time and high mechanical stress. Hybrid DCCBs combine mechanical switches with power electronic devices to achieve fast and reliable interruption, but they have high losses and require complex control. Solid-state DCCBs use only power electronic devices to interrupt the fault current, but they have high cost and large volume (Taherzadeh et al., 2023).

The selection of DCCBs for HVDC systems depends on various factors, such as the system voltage level, fault current magnitude and duration, converter topology, protection scheme, and economic feasibility. For example, for 400V DC systems in data centers, which have low fault current levels and short fault durations, solid-state DCCBs may be preferred over mechanical or hybrid DCCBs because of their fast response time and low arc voltage (X. Song et al., 2021). However, for 380V DC systems in offshore wind farms, which have high fault current levels and long fault durations, hybrid DCCBs may be preferred over solid-state or mechanical DCCBs because of their low losses and high reliability (Tu et al., 2022).

The role of DCCBs in HVDC systems is a topic of ongoing research and development. There are many challenges and opportunities for improving the performance, cost-effectiveness, and standardization of DCCBs. Some of the future trends include developing new materials and technologies for arc quenching and current interruption, designing modular and scalable DCCBs for different applications and voltage levels, integrating DCCBs with other protection devices and communication systems, and testing and demonstrating DCCBs in real HVDC grids.

Table 7. Properties of different types of DCCBs.(Taherzadeh et al., 2023)

Circuit Breaker	Operating Speed (ms)	Fault Current Breaking Capability (kA)	Complexity	Cost ($)
MCB	100-200	10-50	Simple	Low
SSCB	1-10	50-1000	High	High
HCB	5-15	20-500	Medium	Medium

2.6 Reliability

Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. Reliability is one of the most important aspects of data center power distribution architecture, as it directly affects the availability and performance of the IT equipment and services hosted in the data center.

Data center power distribution architecture refers to the design and implementation of the electrical power system that delivers power from the utility grid or backup generators to the IT equipment racks. The power distribution architecture consists of various components, such as transformers, switchgear, UPS, PDU, branch circuits, and power cords(K. M. U. Ahmed et al., 2021).

The reliability of the power distribution architecture depends on several factors, such as:

- the quality and redundancy of the power sources, such as the utility grid and backup generators
- the efficiency and protection of the power conversion and conditioning devices, such as transformers and UPS
- the scalability and flexibility of the power distribution devices, such as PDUs and branch circuits
- the monitoring and management of the power consumption and status of the IT equipment and the power distribution components

Table 8. Availability and Downtimes

Availability (number of 9s)	Downtime per year	Downtime per day
1	36.5 days	2.4 hours
2	3.65 days	14.4 minutes
3	8.76 hours	1.44 minutes
4	52.56 minutes	8.66 seconds
5	5.26 minutes	864.3 milliseconds
6	31.5 seconds	86.4 milliseconds
7	3.15 seconds	8.64 milliseconds
8	315.569 milliseconds	0.864 milliseconds
9	31.5569 milliseconds	0.0864 milliseconds

Table 9. Equipment reliability data (Y. Chen et al., 2022; Shrestha et al., 2018)

Component	Inherent Availability	MTBF (hours)	MTTR (hours)
Diesel Generator	99.997423%	2000	4
Circuit Breaker	99.999989%	1×10^6	2
Bus Bars/Switch Board	99.999210%	4.38×10^6	9
Automatic Transfer Switch	99.999950%	1×10^6	2
3-phase Rectifier	99.990100%	20000	2
3-phase Inverter	99.990100%	20000	2
DC-DC Converter	99.996000%	50000	2
Lead Acid Battery	99.9966667%	240×10^6	8
Isolation Transformer	99.999937%	7.8×10^3	6
Static Bypass Switch	99.997334%	300×10^3	8

Table 10. Reliability of different distribution systems(Shrestha et al., 2018)

Distribution System	MTBF (hours)	MTTR (hours)	Availability (number of 9s)
480V AC 2N	1,243,920	3.73875	5
380V DC 2N	2,058,600	1.6063	6
480V AC 2(N+1)	3,328,800	0.07656	7
380V DC 2(N+1)	3,740,520	0.04488	7
480V AC 2(N+2)	9,995,160	0.01667	9
380V DC 2(N+2)	10,985,040	0.01667	9

The Inherent Availability is the percentage of time that a component is expected to be available, assuming that it is not subject to any failures. The MTBF (Mean Time Between Failures) is the average amount of time that a component is expected to operate before it fails. The MTTR (Mean Time to Repair) is the average amount of time that it takes to repair a failed component.

The Table 9 shows that the most reliable components are the circuit breaker, automatic transfer switch, and isolation transformer, with inherent availabilities of 99.999989%, 99.999950%, and 99.999937%, respectively. The least reliable components are the lead acid battery and static bypass switch, with inherent availabilities of 99.9966667% and 99.997334%, respectively.

The MTBF values for all of the components are in the thousands of hours, indicating that they are expected to operate for a long period of time before failing. The MTTR values are all relatively low, indicating that failed components can be repaired quickly.

The Table 10 presents data on the reliability and repairability of different electrical distribution systems within data centers, categorized into four columns. The "Distribution System" column specifies the electrical distribution system type. The "MTBF" (Mean

Time Between Failures) column indicates the system's average operational duration before failure; for example, the 480V AC 2N system operates for an average of 1,243,920 hours, equating to approximately 143 years. The "MTTR" (Mean Time To Repair) column provides the average repair time for a system, with the 480V AC 2N system requiring about 3.73875 hours for repair. The "Availability" column quantifies system availability in terms of nines; a higher figure denotes greater reliability. For instance, a system with five nines (99.999%) availability is operational 99.999% of the time. According to theTable 10, the 480V AC 2(N+2) system achieves the highest availability at nine nines, indicating minimal downtime annually and daily. In contrast, the 380V DC 2N system records the lowest availability at five nines.

To enhance the reliability of power distribution architectures, data centers can implement several strategies. These include integrating advanced cooling systems to mitigate heat load and bolster thermal stability of the power distribution elements, embracing modular power distribution designs to facilitate straightforward installation, expansion, reconfiguration, and maintenance of the power distribution components, and deploying smart power management systems that offer immediate visibility, control, and optimization of both the power consumption and the operational status of the IT equipment along with the power distribution elements.

Examples of power distribution architectures in data centers designed to improve reliability encompass 380 Vdc architectures, which streamline the power conversion process, enhancing efficiency and reducing complexity in wiring. Additionally, modular PDUs provide a versatile and expandable means for power delivery to densely packed IT racks via a singular, adaptable power source. Moreover, the implementation of overhead power busways eliminates the requirement for wiring beneath the floor, augments airflow within the data center, and simplifies the reorganization of branch circuits.

3 Power Distribution Infrastructures

3.1 Power Distribution Infrastructures Scenarios

Data centers are facilities that house servers and other IT equipment for providing cloud-based computing services. They require efficient power distribution architectures to improve their reliability and reduce their costs. There are two main types of power distribution architectures: Alternating Current (AC) and Direct Current (DC). This report will compare the advantages and disadvantages of these two systems, as well as some hybrid architectures that combine both AC and DC power (Zhang, 2023). Power distribution to data centers can be accomplished using alternating current (AC) or direct current (DC) power. AC power is typically distributed at the local mains voltage of 120 V, 208 V, or 230 V, while DC power is typically distributed at the telecommunication's standard voltage of 48 V or higher voltages such as, 380 VDC, or 400 VDC. The choice of AC or DC power distribution has implications for the efficiency, cost, compatibility, reliability, harmonics, and safety of data centers (Nabih & Li, 2021, 2023; Rasmussen, n.d.-b)

Data center power can be categorized based on different degrees of functionality (Krein, 2017):

- At the facility or building level, the entry point of the main utility supply into the building is established. In North America, facilities often have the option to select either a three-phase mains frequency feed, typically at 480 V, or a direct three-phase distribution feed at 12 kV, with the latter not commonly used internally within most configurations. For data backup purposes, buildings are usually outfitted with an uninterruptible power supply (UPS) that relies on batteries and fuel-powered generators to provide power in the event of utility feed interruptions.
- At the rack level, within systems of high capacity, a three-phase electrical power supply, often at 208 V, is distributed to bulk direct current (DC) power converters. Each converter is dedicated to serving a separate rack. Proceeding to the board level, DC power is supplied to individual server boxes within a rack, which can

then be directly connected to large motherboards, often incorporating an additional stage of DC-DC conversion.

- At the chip level, individual point-of-load (PoL) DC-DC converters situat-ed within a board deliver low-voltage power specifically designed for chips or chipsets, typically involving three to five different voltage values for precise power management.
- Finally, at the internal level, some integrated circuits (ICs) come with built-in energy management features, further optimizing the power dis-tribution architecture within data centers across multiple layers, from the facility level down to the individual chips, ensuring both efficiency and reliability in power supply and management.

Nevertheless, it is important to acknowledge that ultimately, all the energy supplied to a data center is released as heat, with the energy utilized for information output being little. It is necessary to transfer all of the incoming power to the environment. Conversion loss refers to the additional energy that needs to be extracted from the plant.

In order to optimize distribution efficiency, it is often advisable to maintain the voltage at the highest possible level until it reaches the end user, since this helps minimize electrical loss. For instance, if a rack is taking 30 kW of power from a 208 V three-phase supply, it needs to be configured to handle a 100 A service with sufficient headroom. By switching to a direct feed at 600 V dc, the current needs are reduced to approximately 50 A. This decrease in current leads to a reduction in copper losses and relative voltage decreases. It should be noted that a power of 30 kW at a voltage of 48 V requires a current of over 600 A, which in turn necessitates the use of substantial copper bus-work. To minimize energy usage, it is most effective to transmit the greatest voltage available deep into the system, hence avoiding the need for conversion. Therefore, it is possible to distribute power at the rack level using boards in order to eliminate the need for power conversion at the board level. The rectification stage, commonly found in the rack, can be relocated near the building entrance (N. He et al., 2019; Kim, 2016).

3.1.1 AC Infrastructures

AC power is the standard electricity format that comes from a power plant. The direction of the current reverses, or alternates periodically, 60 times per second (in the U.S.) or 50 times per second (in Europe). AC power can be easily transformed to different voltage levels using transformers, which makes it easy to transport over long distances. However, AC power also involves more conversions and losses when used by data center equipment, which reduces its efficiency and generates heat.

AC power distribution has been the dominant choice for data centers for decades, mainly because it is compatible with the existing power grid and most IT equipment. However, AC power distribution requires multiple conversion stages between the grid and the IT devices, which introduce losses and inefficiencies. A typical AC power distribution system involves the following conversion stages through Figure 1 (Huber et al., 2022):

- AC-DC rectification at the uninterruptible power supply (UPS) to charge the batteries and provide backup power in case of grid failure
- DC-AC inversion at the UPS to convert the battery power back to AC
- AC-AC transformation at the (PDU to step down the voltage to the level required by the IT equipment
- AC-DC rectification at the server PSU to convert the AC input to DC for the internal components

Each conversion stage has an efficiency of about 90% to 95%, which means that about 5% to 10% of the input power is lost as heat. The cumulative efficiency of an AC power distribution system can be as low as 50% to 60%, depending on the load and operating conditions. Moreover, each conversion stage generates harmonics, which are distortions in the waveform of the AC voltage and current. Harmonics can cause overheating, interference, and damage to electrical equipment and wiring (Aamir et al., 2016; Huber et al., 2022; Pratt et al., 2007).

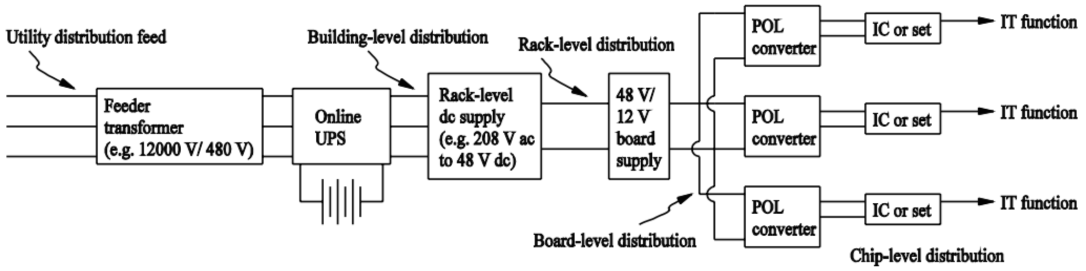

Figure 18. Typical conversion sequence in an ac data center architecture (Krein, 2017)

In Figure 18, power undergoes four conversions from the alternating current (ac) mains to the integrated circuit (IC) level. The efficiency of the online UPS can reach up to 97% when the batteries are fully charged. The efficiency of the rack-level supply is normally around 95%. Board-level supplies are generally considered to have an efficiency rating of approximately 93% to 95%. Power over Ethernet (PoL) converters provide significant challenges due to their low output voltage. It is generally recommended to expect an efficiency of approximately 88%. Approximately 75% to 77% of electrical energy is effectively delivered to the ICs and chipsets.

In an AC power data center, the power is distributed to the facility from utility Ac with MVAC. Then this power is stepped down to 690 VAC or 400 VAC via transformers for distribution, then next step AC to DC conversion in rack level for use by servers and other IT equipment. An uninterruptible power supply (UPS) and energy storage systems such as batteries are used as power backup for power interruption and disturbances. The incoming AC power has to be converted to DC for storage. When power interruption occurs, power backup converts stored DC power to AC power. The power is further transmitted to PDUs and then to servers and IT equipment placed in racks (Y. Chen et al., 2023; Huber et al., 2022). MVAC systems can reduce the number of transformers and cables, which can lower the capital cost and improve the reliability of the system. However, MVAC systems also require more complex protection devices and safety measures, which can increase the operational cost and complexity of the system.

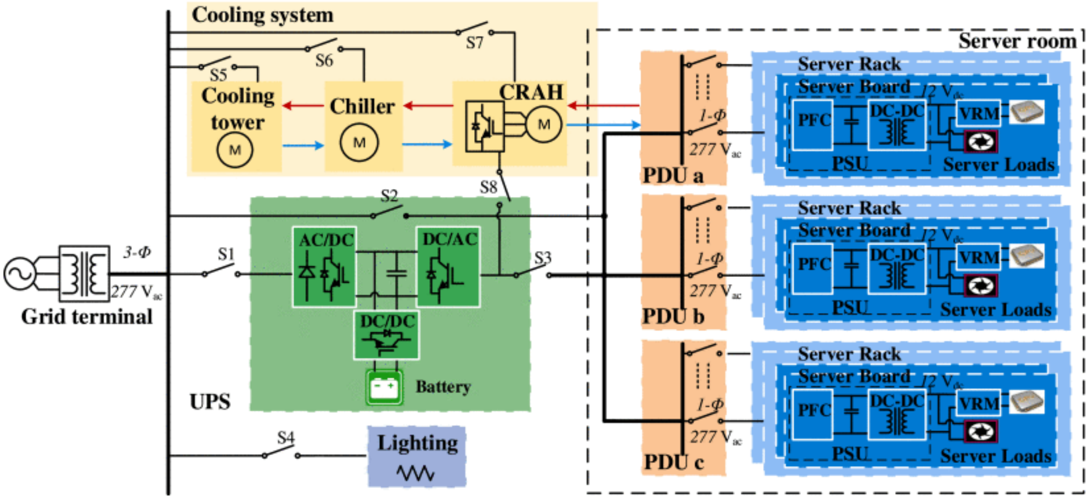

Figure 19. Typical structure of a data center ac power distribution system **(Sun et al., 2022)**

3.1.2 DC Infrastructures

DC power is an electricity format that comes from batteries and sources such as solar cells and fuel cells. The current flows in a linear and direct manner, and does not oscillate between positive and negative terminals. DC power can be more efficient than AC power for data center equipment, as it eliminates the need for conversions and reduces losses and heat generation.

Some data centers are being developed with direct current (DC) distribution, operating at voltage levels as high as 600 volts. Figure 20, shows a sample block diagram. This enhances the effectiveness of building-level conversion and effectively substitutes the online UPS with a more straightforward active battery interface. Directly providing this high-voltage dc supply to the racks improves the efficiency of rack-level conversion. The reported enhancements achieved a 7% decrease in energy consumption, while the actual outcomes are expected to be even more favourable when considering the benefits of the UPS system (Krein, 2017).

Further enhancement is achievable by supplying power at a voltage of 48 V or higher at the board level. Despite scepticism from some, 48 V systems have a long history of use in telecoms power and have been demonstrated to improve the reliability of power systems.

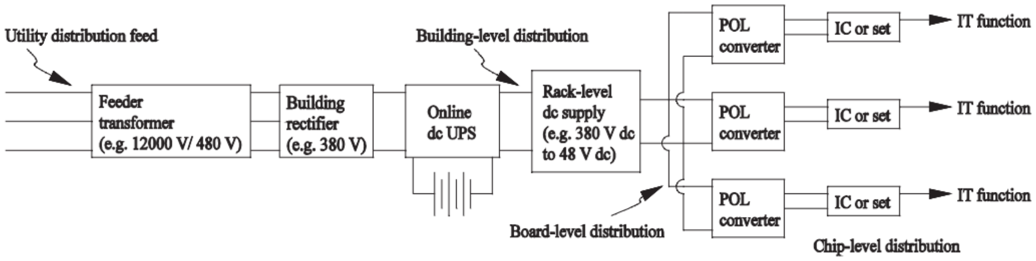

Figure 20. Typical conversion sequence in a dc data center architecture(Krein, 2017)

DC power distribution has been proposed as an alternative to AC power distribution in data centers, based on the assumption that it can eliminate or reduce some of the conversion stages and improve efficiency. A DC power distribution system involves fewer conversion stages than an AC system, depending on the voltage level used. A typical DC power distribution system involves the following conversion stages (Al-Harbi et al., 2019; Rasmussen, n.d.-a, n.d.-b; Sun et al., 2022):

- AC-DC rectification at the rectifier to convert the grid power to DC
- DC-DC transformation at the BDCBB (battery distribution circuit breaker bay) or FAP (fuse alarm panel) to step down the voltage to the level required by the IT equipment
- DC-DC conversion at the server PSU to regulate the DC input for the internal components

There are also different variants of DC power distribution architectures, such as low-voltage DC (LVDC) and medium-voltage DC (MVDC). LVDC systems use 48V DC or 12V DC for both distribution and IT equipment, while MVDC systems use higher voltages such as 380V DC or 400V DC for distribution and step down to lower voltages at the rack level. MVDC systems can reduce the number of converters and cables, which can lower the capital cost and improve the reliability of the system. However, MVDC systems also require new protection devices and standards, which are still under development (Chrysostomou et al., 2020; Knabben et al., 2020; Shrestha et al., 2018).

Data center power distribution architectures vary across different levels, including utility, facility, and rack levels, allowing for diverse configurations. This variation enables the assessment of a power system's efficiency and reliability based on the chosen configurations. In this thesis, the focus is on exploring various power distribution architectures, such as the typical AC distribution, alongside 380VDC and 400VDC architectures, among others. The aim is to evaluate their efficiencies and stability under specific conditions. The study extends to examining how power systems and research infrastructures can achieve greater efficiency, particularly in terms of Power Usage Effectiveness (PUE) and other sustainability-related energy metrics.

3.1.2.1 380VDC/400VDC Facility level:

As you can see in Figure 21., which uses 380 V DC as the standard voltage for distribution, and Figure 22. Which has 400 VDC in Facility level and 48 V DC in rack level as the standard voltage for device input. This option eliminates two conversion stages: facility to rack and rack to device. The grid supplies medium-voltage AC power to the data center facility, which uses rectifiers to convert it to 380 V DC for Figure 21. For Figure 22., the 400 VDC power is then distributed to busbars located in or near each rack of IT equipment. The IT devices use internal converters to step down the 400 V DC power to 48 V DC or lower for their internal components.

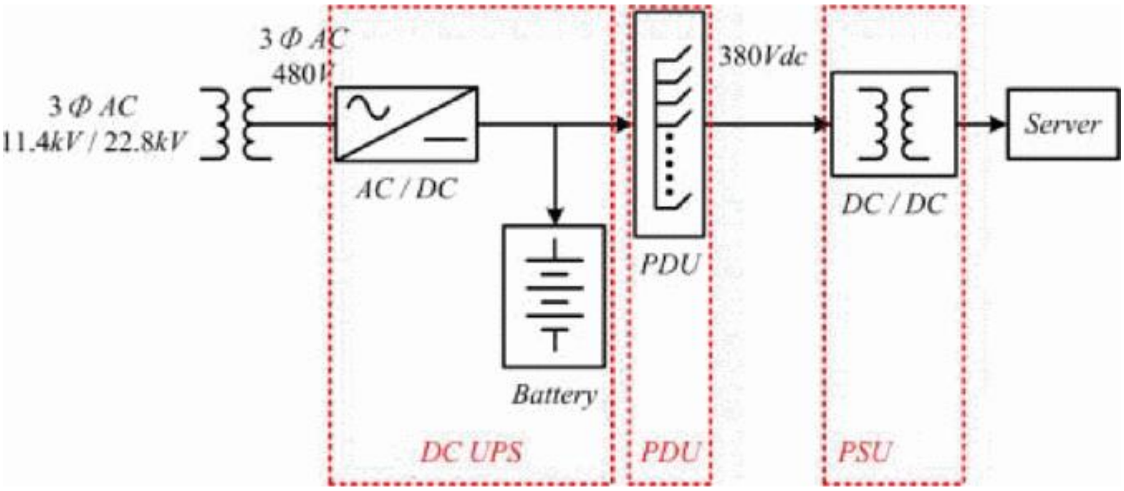

Figure 21. 380VDC Facility Level. (D.-F. Huang et al., 2015)

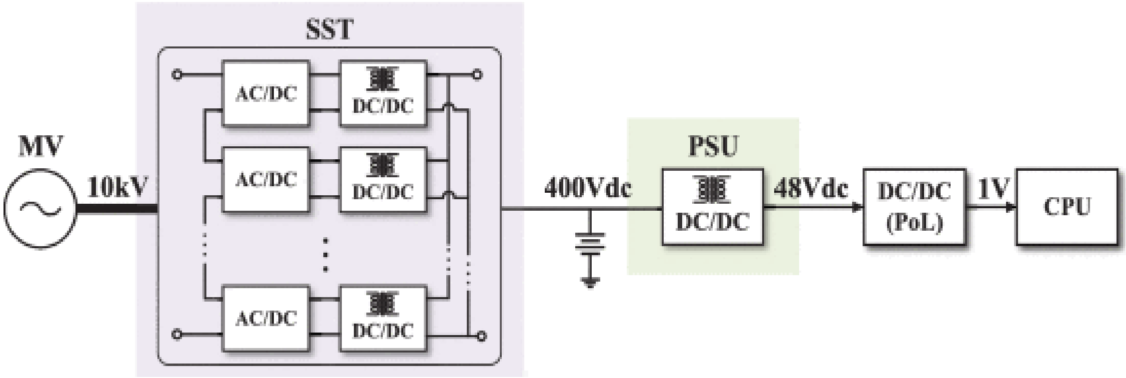

Figure 22. 400VDC Facility Level.(Y. Chen et al., 2023)

For these power distribution architectures, they are changing into changing UPS in their Facility level to check efficiency in the output. The explanation of these figures is here:

- AC-DC with PFC: In Figure 23(a), this is the most conventional of the three architectures. In this configuration, 13.2 kV AC power enters the system and is converted to DC power using a rectifier. The DC power then undergoes filtering to remove unwanted harmonics before being distributed throughout the data center at ±400 V. Finally, point-of-load DC-DC converters step down the voltage to 48 V, which is the typical voltage used by data center equipment.
- 12-pulse rectifier + Active filter: In Figure 23(b), this architecture is similar to (a) but uses a 12-pulse rectifier to convert AC to DC power. A 12-pulse rectifier offers lower harmonic distortion compared to a 6-pulse rectifier, potentially reducing the need for filtering equipment.
- Solid-state transformer (SST) + DC-DC converter: In Figure 23(c) , this architecture utilizes a solid-state transformer (SST) to convert 13.2 kV AC to a medium voltage DC (MVDC) at ±400 V. MVDC distribution offers several potential benefits over traditional AC distribution, including reduced energy losses and improved efficiency. However, SSTs are a relatively new technology, and more research is needed to determine their long-term reliability and cost-effectiveness.

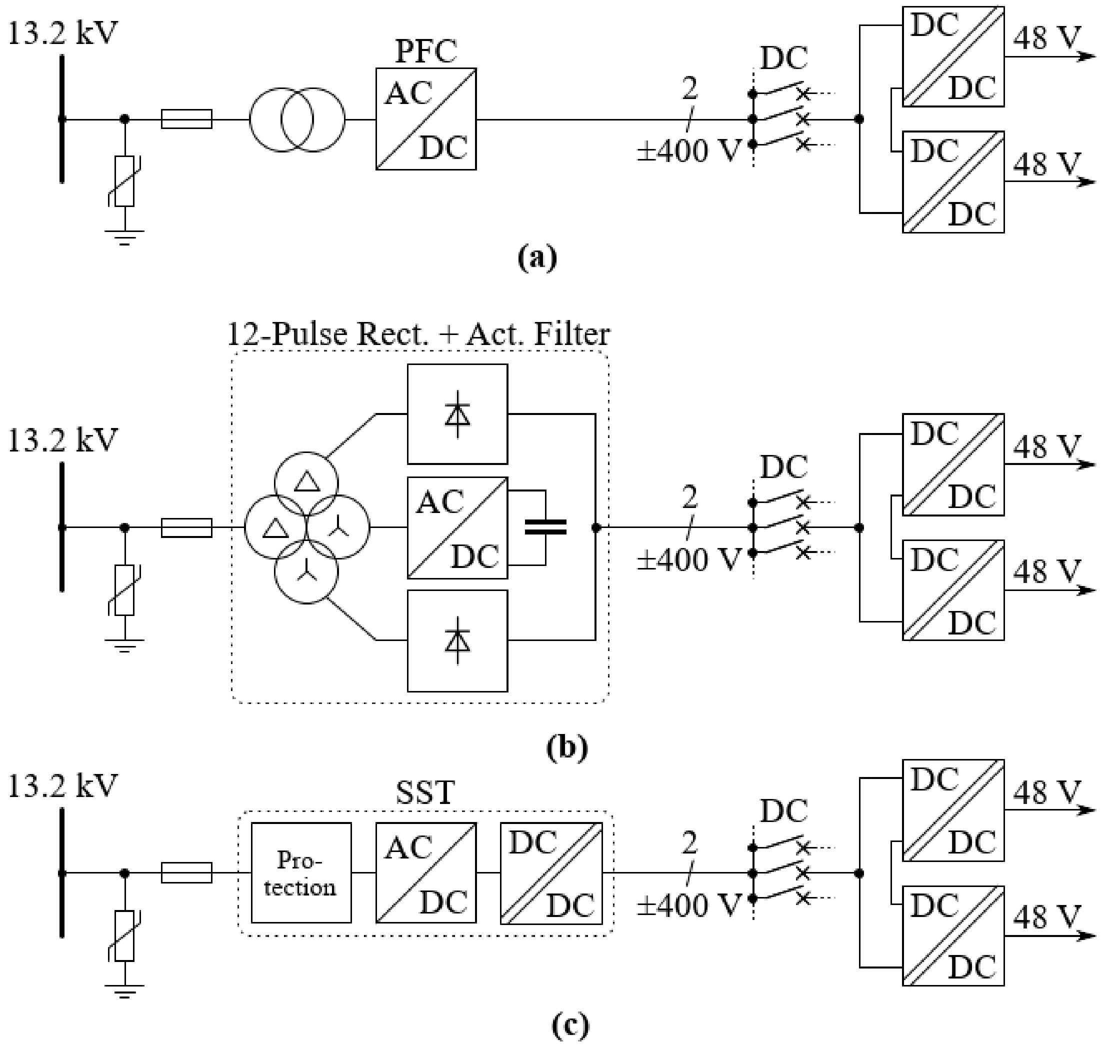

Figure 23. a) 400VDC distribution with MVAC-LVDC conversion employing a LFT and a centralizedSiC PFC rectifier, (b) a 12-pulse rectifier and an active filter (AF) for powerfactor correction, (c) a solid-state transformer (SST).

3.1.2.2 48VDC Facility level:

This option uses 48 V DC as the standard voltage for both distribution and device input. This option eliminates all conversion stages except for one: grid to facility. The grid supplies medium-voltage AC power to the data center facility, which uses rectifiers to convert it to 48 V DC. The 48 V DC power is then distributed directly to the IT devices, which use it internally without any further conversion. This option is similar to the power distribution system used in telecom central offices, which have a long history of high reliability and availability.

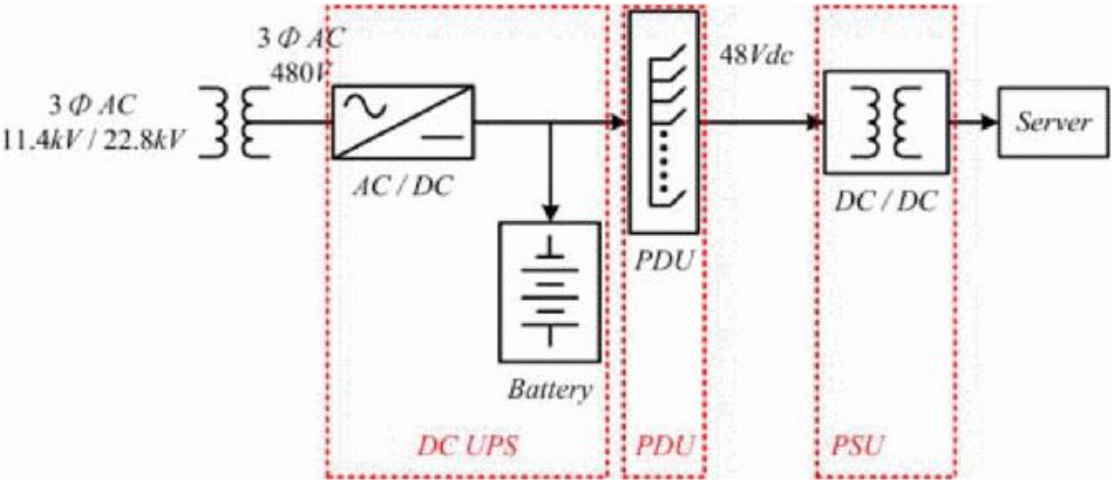

Figure 24. 48VDC Facility Level(D.-F. Huang et al., 2015)

3.1.3 Hybrid Infrastructures

Hybrid power distribution architectures combine both AC and DC power in different ways to achieve optimal performance and efficiency. For example, a hybrid architecture can use AC power for distribution and backup, but use DC power for IT equipment. This can reduce the number of conversions and losses while maintaining compatibility with existing infrastructure. Another example is a hybrid architecture that uses DC power for distribution and backup, but uses AC power for IT equipment. This can leverage the benefits of high-voltage DC transmission while maintaining compatibility with existing IT equipment (Barthelme et al., 2017; Y. Chen et al., 2023).

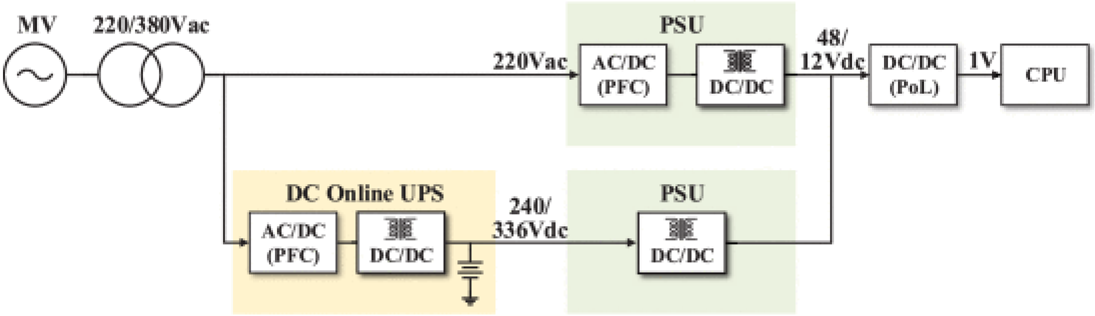

Figure 25. Hybrid Power distribution architecture(Y. Chen et al., 2023)

One specific hybrid architecture that has been proposed is the 220 VAC/336 V DC system. This system uses a theoretical DC UPS that converts incoming medium-voltage AC power to both 220 VAC and 336 V DC outputs. The 415 V AC output is used for IT equipment that requires 230 V AC input, while the 380 V DC output is used for IT equipment that supports 380 V DC input. This system can eliminate the need for PDUs and reduce the number of conversions and losses. However, this system also requires new IT equipment that can accept both 415 V AC and 380 V DC inputs, which are not widely available yet.

4 Comparative Analysis

The aim of this section is to analyse the various topologies and architectures to determine which ones offer the best efficiency for our data center. This analysis begins with an assessment of voltage ranges and then moves on to evaluate the types of Uninterruptible Power Supplies (UPS) that could be utilized, as well as the components involved and their respective costs.

Following this, I create a table comparing different power supplies, focusing on their intersections. The analysis concludes by using these different components to construct various types of power distribution market architectures. The efficiencies of these architectures are then evaluated based on different aspects, such as the facility level, transformers, UPS, distribution wiring, and power supplies.

Ultimately, the section concludes by summarizing the overall efficiency of the different power distribution architectures examined, offering insights into the most efficient designs for data center operations.

4.1 Voltage Ranges

The voltage level of the power supply in data centers depends on several factors, such as the country standards, the type of equipment, and the efficiency requirements. In general, higher voltage levels reduce the current and thus the losses in transmission lines and transformers. However, higher voltage levels also increase the risk of electrical shocks and require more insulation and protection devices.

The most common voltage levels used in data centers are 400 V AC, 380 V DC, 208 V AC, 48 V DC, and 12 V DC. 400 V AC is widely used in Europe and Asia as the standard low-voltage level for distribution and equipment connection. 380 V DC is an emerging standard for data center power distribution that aims to improve efficiency and reliability by eliminating conversion losses between AC and DC. 208 V AC is commonly used in North

America as the standard low-voltage level for distribution and equipment connection. 48 V DC is widely used in telecommunications equipment as a standard voltage level for battery backup systems. 12 V DC is commonly used in servers and other IT equipment as a standard voltage level for internal components.

Table 11. Voltage Ranges for different power systems

Type	Voltage Range
LVAC	Typically, 230V or 400V
LVDC	Up to 1100V
MVAC	Typically, 200V to 240V
MVDC	1.5kV to 100kV
HVAC	Typically 275kV and 400kV5, up to 765kV
HVDC	100kV to 800kV

4.2 UPS and their properties

In this section, we explore Uninterruptible Power Supplies (UPS) and their properties as outlined in Table 12. My work involves analysing various UPS models, focusing on key attributes such as their power capacity, switching frequency, and efficiency levels. Through this analysis, we identify the most efficient UPS models.

One notable finding is the ZVS (Zero Voltage Switching) hard switching UPS, which operates at a 150 kHz frequency and demonstrates an efficiency of 97.10%. Another significant discovery is the ZVS (Zero Voltage Switching) 2 level hard switching UPS, operating at a 150 kHz frequency. This model stands out with an efficiency of 97.10%, the highest recorded in my analysis.

These findings, derived from a detailed examination of different UPS models and their efficiencies, are crucial for optimizing power distribution architecture. By selecting the UPS with the best performance metrics, we can enhance the overall efficiency of power distribution systems. This approach underscores the importance of thorough evaluation and selection of UPS models based on their operational efficiencies.

Table 12. Different UPS Models(Y. Chen et al., 2023; Delta, n.d.; Eaton, n.d.-a)

Topology (Product)	Wiring	Power	Vac	Switch. Freq.	50% Eff	100% Eff
ABB PowerScale	3P4W	10 kVA	230 V	-	-	95.50%
Delta HPH-40K	3P4W	40 kVA	230 V	-	-	96.00%
ZVS 2-Level	3P4W	10 kVA	220 V	150 kHz	97.50%	97.10%
Hard-Switching 2-Level	3P4W	10 kVA	220 V	150 kHz	94.30%	94.00%
ZVS 2-Level	3P4W	50 kVA	220 V	15 kHz	96.46%	96.18%
Hard-Switching 2-Level	3P4W	50 kVA	220 V	15 kHz	94.30%	93.95%
Hybrid T-Type	3P4W	50 KVA	220 V	7.2 kHz	97.20%	97.00%
Eaton-93PM	3P4W	50KVA	480 V	-	-	97.00%
Delta DPH	3P4W	50KVA	230 V	-	-	96.50%

4.3 Data Center components and their cost comparison

In Table 13, the analysis focuses on the components provided by two major companies in the data center industry, Siemens and Schneider Electric. This examination involves a detailed comparison of various components, assessing their properties, price ranges, and suitability based on specific customer requirements. The evaluation seeks to understand how each company's offerings align with the diverse needs of data center operations, emphasizing the importance of selecting components that not only meet technical specifications but also offer value within the given price range. This approach ensures that recommendations for data center components are tailored to the unique demands of customers, facilitating informed decision-making in the procurement process.

Table 13. Components and their costs

Component	**Siemens**	**Schneider Electric**
AC Generation	SGen-100A/1000A series, 25-370 MVA, $1.5-15 million	GT Series, 25-250 MW, $1.2-12 million
Battery (0.5 h)	SITOP UPS500S, 2.5-40 A, $200-800	APC Smart-UPS, 750-3000 VA, $300-1500
AC Transformer	SITRANS F M MAG 5000, 0.2-600 m3/h, $1000-5000	PowerLogic PM5000 series, 0.333-6000 A, $500-3000
AC/DC Rectifier	SITOP PSU8600, 24-28 V, 40-960 W, $400-2000	Galaxy VS, 10-150 kW, $5000-30000
DC/AC Inverter	SINAMICS G120, 0.37-250 kW, $500-10000	Conext SW, 3.8-7.0 kW, $1000-2000
DC/DC Converter	SITOP DC UPS, 24 V, 6-40 A, $200-800	Conext MPPT 60 150, 12-60 V, 150 A, $600-1000
12.7kV AC Cable	8BT2 air-insulated medium-voltage switchgear, $1000-5000 per meter	Premset SSIS, $800-4000 per meter
10kV DC Cable	8DJH 36 gas-insulated medium-voltage switchgear, $1200-6000 per meter	GHA gas-insulated switchgear, $1000-5000 per meter
480V AC Cable	SIVACON S8 low-voltage switchboard, $500-2500 per meter	Okken low-voltage switchboard, $400-2000 per meter
380V DC Cable	SIVACON 8PS busbar trunking system, $400-2000 per meter	Canalis busbar trunking system, $300-1500 per meter
208V AC Cable	SIVACON S4 low-voltage power distribution board, $300-1500 per meter	Prisma low-voltage switchboard, $200-1000 per meter
12.7kV AC Busbar	ALPHA 3200, $500-2500 per meter	I-Line, $400-2000 per meter
10kV DC Busbar	SIVACON 8PS BD2, $400-2000 per meter	Canalis KN, $300-1500 per meter
208V AC Busway	SIVACON 8PS LI, $200-1000 per meter	Canalis KTA, $100-500 per meter
380V DC Busway	SIVACON 8PS LD, $300-1500 per meter	Canalis KS, $200-1000 per meter
ACCB	3WL air circuit breakers, 630-6300 A, $1000-10000	Masterpact MTZ air circuit breakers, 630-6300 A, $800-8000
DCCB	3WA air circuit breakers, 630-6300 A, $1200-12000	Masterpact NW DC circuit breakers, 800-4000 A, $1000-10000
GaN	SINAMICS S210, 0.4-7 kW, $400-2000	Altivar Process ATV6000, 0.75-1200 kW, $500-25000

4.4 PSU and their Properties

In this section for Table 14, I examine various types of Power Supply Units (PSUs), focusing primarily on two categories: single-stage PSUs and two-stage PSUs. This study delves into their differing configurations and how these are utilized effectively within the context of data center operations, specifically on the right side where PSUs are predominantly installed.

The analysis extends to the exploration of multiple PSUs and their stages, emphasizing that the efficiency of these units varies significantly based on their stage configuration. Such variations are crucial as they directly influence the overall performance and efficiency of power distribution architectures within data centers.

Furthermore, the selection of PSUs is informed by their efficiency across different conversion stages, underscoring the importance of choosing the right combination of PSU characteristics to match the specific requirements of the power distribution architecture. This careful consideration ensures that the chosen PSUs enhance the efficiency and reliability of data center operations.

Table 14. comparison of different power supplies for rack level.(M. H. Ahmed et al., 2017, 2021; Y. Chen et al., 2023)

Topology	**Input Voltage (V)**	**Maximum I-out**	**50% Effi.**	**100% Effi.**	**Height (mm)**	**Current Density (A/mm²)**	**Switching Frequency (kHz)**
LLC+Buck	48-6-1.8	530	>93.5%	89	NA	NA	600
LLC+Buck (MPS)	48-4.8-0.8	333	NA	86.4	7.72	0.064	350
SC+Buck (ADI)	48-12-1	50	>90.7%	>88.1	7.72	0.064	350
SC+SCB	48-24-1	150	>90.5%	>86.2	20	0.346	417
SC+Buck	48-8-1	780	>86.5%	>79.2	16.65	1	1000
SC+SCB	48-24-1	640	>91.8%	>84.4	11	0.311	417
Buck-Boost + LLC (Vicor)	48-48-1	120		>90.2%	6.73	0.202	1025
LLC+Buck (Sigma)	48-1	80	>94%	>92.5	4	0.127	600
Current Doubler (Bel Power)	48-1	70	>92%	>90.5	12.7	0.184	242
Current Doubler	48-1.8	160	>92.7%	>90%	4.45	0.152	600
12-Level SCB On-Chip	48-1	8	>86%	>76%	2.6	0.031	2500
Hybrid-SC	48-1	270	>91.5%	>87.7%	6.45	0.142	280

4.5 Comparison of different Power distribution architectures

In the final section of the comparative analysis in Table 15, I delve into various Power Distribution Architectures, focusing on their distribution mechanisms at both the facility and rack levels. This analysis covers a range of distributions, including 230 Volt AC, 400 Volt AC, 690 Volt AC, ±400 Volt DC, and 384 Volt DC. At the rack level, distributions vary from 400 to 48 Volt DC, among others, showcasing the diversity in power delivery methods across different data center environments.

This section outlines four critical stages of standard distribution architecture: the transformer stage, UPS stage, distribution wiring stage, and power supply stage. The primary objective is to evaluate the efficiencies of these distribution architectures, drawing insights from various research papers and studies previously conducted within the scope of my thesis and broader comparative analysis.

A key finding from this study is the identification of the ±400 Volt DC architecture as particularly effective at the facility level, with a transition towards 48 Volt DC at the rack level. This configuration has been highlighted for its superior overall efficiency of 92.31%. While numerous combinations of power distribution exist, this particular arrangement stands out as the most optimal for implementation within my architectural design.

The efficiency metrics utilized in this analysis are derived from a comprehensive review of existing literature and my own previous research, underscoring the importance of evidence-based decision-making in the design of power distribution systems for data centers. Through this methodical approach, the research identifies the best combinations of power distribution architectures, aimed at enhancing the efficiency and reliability of data center operations.

Table 15. Comparison of Power Distribution Infrastructure(Y. Chen et al., 2023; Huber et al., 2022; Pratt et al., 2007)

Topology	**Facility Level**	**Rack Level**	**Trans-former EFFI.**	**UPS**	**Distribution wiring**	**Power supply**	**Overall Efficiency**
400/230 VAC	230 VAC	-	99.2%	96.20%	99.50%	90.25%	86.39%
400VAC	400VAC	400/48VDC	99.2%	99%	98.90%	94.00%	91.3%
690VAC	690VAC	±600V/48VDC	99.2%	99%	99.6%	94.00%	91.9%
±400VDC	±400VDC	±400VDC/48VDC	99.2%	99%	99.7%	94.00%	**92.03%**
±400VDC	±400VDC	±400VDC/48VDC	-	98.5%	99.7%	94.00%	**92.31%**
380 VDC(Conventional)	380 VDC	-	99.2%	96.00%	99.50%	91.75%	86.93%
400 VDC	400 VDC	48 to 1 VDC	-	98.20%	99.50%	94.00%	91.84%
400 VDC(SST)	400 VDC	48-12-1 VDC	-	98.20%	99.50%	90.00%	87.94%

5 Discussion and Conclusion

This thesis conducts a thorough review of power supply systems in data centers, focusing on AC, DC, and hybrid infrastructures. It highlights a movement towards minimizing power conversion stages to enhance overall efficiency and reliability, spotlighting DC architectures as particularly promising due to their ability to bypass the DC/AC stage in UPS and the AC/DC stage in PSU. The comprehensive literature review of electricity consumption, carbon emissions and sustainability, energy and performance metrics and sector coupling.

The primary objective of this study is to evaluate the advantages and disadvantages of each power distribution architecture, with a particular emphasis on quantifying the benefits and cost savings offered by DC infrastructures compared to AC infrastructures. The analysis incorporates various aspects, including safety, reliability, and efficiency, among others, to support the argument that DC data centers present numerous benefits.

The second part about through review of cutting-edge technologies used data center power distribution architecture. The stages in data center infrastructure becoming more efficient. This efficiency gain is further enhanced by recent advancements in UPS technologies that allow for direct connection to the MV grid at the facility level through efficient SSTs and 12-pulse rectifier with active filtering. Additionally, this thesis discusses the latest developments in converter technology within data center power supply systems, including ZVS technologies and IGBT switches for AC and DC conversions through-fats swithing, as well as 48 VDC converters for server power supplies. These innovations aim to reduce device stress and increase operating frequency, thereby improving the efficiency, power density, and dynamic performance of converters.

Acknowledging the substantial and growing power consumption of data centers, the paper underscores the critical importance of enhancing the efficiency of data center power supply systems. I also found that saving energy and reducing carbon emissions in data centers necessitate improvements at both the system architecture level and across all stages of power conversion, from the grid edge to onboard processors.

In the conclusion, the research encapsulates a comprehensive analysis of AC and DC power distribution infrastructures in data centers, aiming to identify which method offers superior efficiency, reliability, and cost-effectiveness. This is crucial for supporting the sustainable transition and environmental stewardship of global infrastructure. This research is grounded in three key questions that examine the differences between AC and DC distribution, their operational mechanisms, and their impact on electricity consumption and carbon emissions. Through a detailed literature review, the thesis explores how each distribution method affects global sustainability efforts, highlighting the potential of renewable energy sources in DC systems to minimize conversion stages, reduce carbon emissions, and enhance energy independence.

A critical comparison indicates that DC architectures typically have fewer conversion stages than AC systems, leading to higher efficiency levels. Despite this, the dominance of AC-compatible components poses challenges for DC implementation in industrial condomain such need for compatible components for DC power infrastructure. Nevertheless, the thesis identifies significant potential for DC distribution in future applications, especially in sector coupling, which could improve grid stability and integration with the heating sector. By adopting DC systems, data centers could lower component costs and enhance operational reliability, making DC distribution a viable pathway to a more sustainable and efficient power infrastructure in the digital era.

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