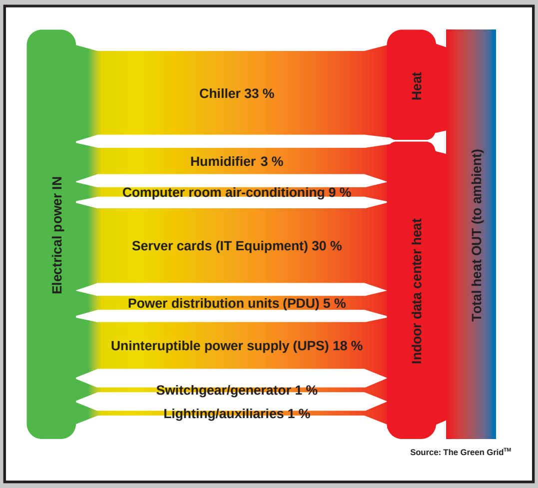
Briefing Paper

Leonardo
ENERGY

DC power distribution for server farms



Source: The Green Grid™

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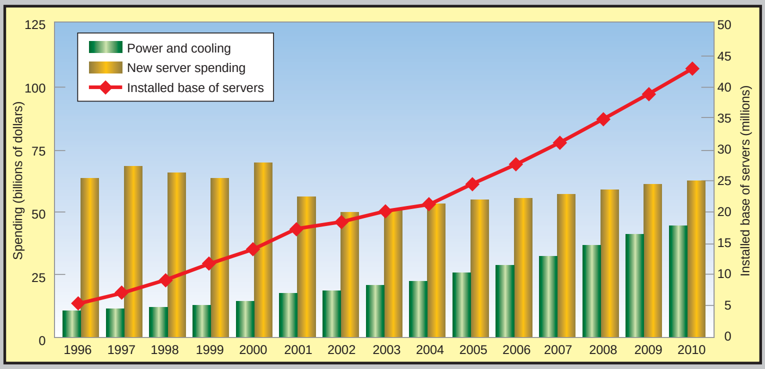

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DC power distribution for server farms

Abstract

Data centers, also known as server farms, are already storing most of the world's digital information. The availability of this data is of crucial importance to data center customers as an unreliable data service will not survive the fierce competition. A reliable power supply and distribution architecture immediately draws the attention in this regard. Furthermore, data centers consume large amounts of electrical energy in trying to keep up with the energy demand associated with the rapid performance increase of the server technology itself. However, increasing energy prices and political pressure are forcing data centers to re-evaluate their energy consumption and increase their electrical efficiency to remain profitable as well as to adhere to possible environmental legislation.

This paper investigates the reliability and efficiency of an AC power distribution architecture found in typical data centers. The application of a DC power distribution architecture is then proposed as an efficient method of power delivery within a data center. This concept is inspired by the absence of reactive power, the possibility of the efficient integration of small-distributed generation units and the fact that, internally, all the loads operate using a DC voltage. A comparison is then made between the AC and DC power distribution architectures as regards reliability, efficiency and their susceptibility to introducing emerging technologies for supporting on-site electrical power generation and storage to achieve a more sustainable system with less emissions.

The investigation reveals that the reliability and the efficiency of a typical power distribution architecture can be improved by decreasing the number of power conversions required within the crucial current path from the source (public grid) to the load (server card). Yet, reducing the power conversions as far as a single point of conversion has an adverse effect. The reliability is reduced as it makes the power distribution more vulnerable to failure. Implementing a redundant distribution architecture solves this vulnerability. In this regard the DC power distribution architecture has the most advantage as it only requires two power conversions as opposed to four for an AC power distribution architecture. Efficiency improvements ranging from 10 to 20% have been reported in the literature. Furthermore, it has been found that DC power distribution has the most advantage for the connection of emerging technologies for on-site power generation and energy storage as a significant amount of this equipment delivers power in DC or high frequency AC, which requires an intermittent DC conversion when connecting to a conventional AC distribution system.

Introduction

The previous *information age*[1] has spurred a tremendous growth in telecommunication in order to propagate, debatably, the single most important commercial resource of our time: *information*. In the current *intangible economy age*[2] the focus has shifted to not only propagating, but also capturing this valuable resource and making it accessible around the clock in a *reliable* manner. Hence came forth the *data center*, also referred to as a server farm or, when dedicated to providing Internet-related content, an Internet Data Center (IDC).

These data centers store large amounts of (digital) information, ranging from personal holiday photographs, hotel reservations, credit card operations to critical information for business and industry. The (continuous) availability of such data centers, as is the case for telecommunication providers, needs to be perfect as interruptions in service, particularly when it affects the customer's revenue and service to their (own) customers, could mean losing business customers permanently to competitors [1]. The cost of such interruptions could escalate rapidly, as shown in Table 1. *In this regard the reliability of the electrical power supply and its distribution within the data center is the most crucial aspect.*

Industry	**Average cost of downtime (US $/hour)**
Cellular communications	41,000
Telephone ticket sales	72,000
Airline reservations	90,000
Credit card operations	2,580,000
Brokerage options	6,480,000

Table 1 Costs of power outages,
according to the U.S. Department of Energy's Strategic Plan for Distributed Energy Resources [2]

It is therefore not uncommon for data centers to install primary and/or alternate power feeders that serve *only* the data center and run directly from the utility substation to the data center. In extreme cases they are served directly from the utility's transmission system instead of a distribution substation to eliminate many of the reliability and quality problems associated with service from a distribution system, although this comes at a significantly higher price due to the cost of the higher voltage components and their physical size [3].

It is therefore clearly evident that reliability enjoys a high priority in data centers.

Furthermore, since the inception of the Internet data centers have not only grown at an enormous rate in numbers (Figure 1): from 6 million servers being used worldwide in 1996 to 28 million in 2006 and 43 million servers expected to be used in 2010[3], but also in power demand. The cost of powering and cooling servers (Figure 1) has increased from an estimated 11 billion US dollars in 1996 to 28 billion US dollars in 2006 with an estimated 42 billion US dollars in 2010[3], establishing data centers' reputation as ferocious consumers of energy.

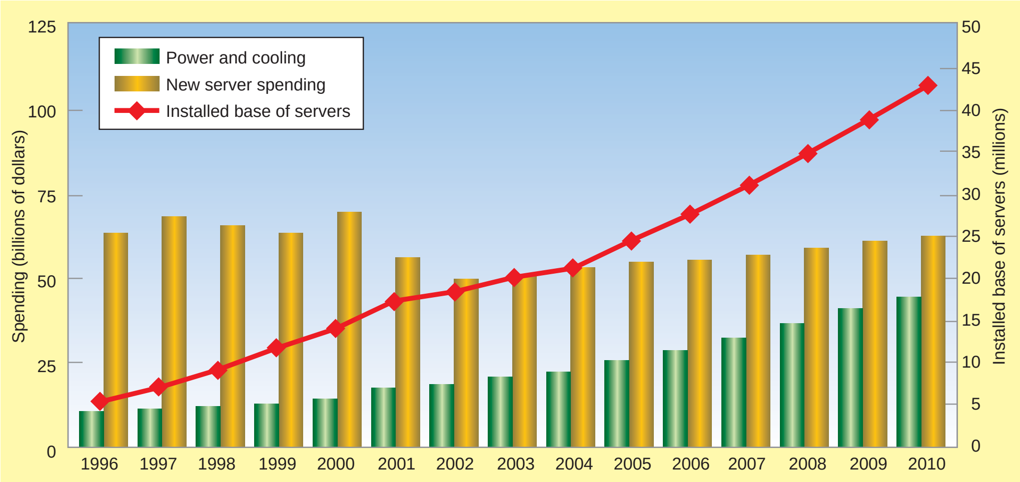

Figure 1 The cost of powering and cooling servers has increased during the last decade and will increase steadily during the next few years, according to market research firm IDC [4]

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[1] Information age is a term applied to the period between 1980 and 1992 where information rapidly propagated.

[2] Intangible economy is a form of capitalism in which intangibles, such as creativity and new knowledge, play the parts that raw materials, factory labor and capital played under industrial capitalism, according to Luis Suarez-Villa, in his 2000 book *Invention and Rise of Technocapitalism*.

[3] According to IDC, a market research firm [4].

The reason for this drastic increase in power consumption is primarily due to the way in which computer processors have historically been designed [5]: to maximize performance at all cost[4]. Higher processor performance leads to more generated heat, in itself increasing the power consumption, but then it subsequently also requires additional power for cooling. This increases the overall power consumption at double the rate.

Not only do the processors generate wasted heat that needs to be cooled, the multitude of implemented power supplies - responsible for proper power processing at various stages of the power distribution - also generate wasted heat that contributes significantly to the overall power consumption. Commonly used power supplies have a typical efficiency of 65%[5] whereas units with efficiencies of 90% or better exist, yet the additional price associated with implementing more efficient components in a power supply results in the implementation of cheap but inefficient power supplies at the cost of power consumption [6]. The significant number of power conversion stages in the overall power distribution architecture (typically 4 or more) increases the power consumption even further.

It is therefore clearly evident that efficiency has not been considered a high priority in data centers, yet increasing energy prices as well as political pressure is making it a high priority.

From the above introduction one can conclude that the power distribution architecture of a data center is of significant importance as regards both its reliability and efficiency, and both are considered a high priority today. Therefore, this paper investigates a typical AC power distribution architecture and compares it to a few promising DC power distribution alternatives. The focus lies strongly on the efficiency and reliability offered as well as the ability to support emerging power generation and storage technologies. The latter will reduce emissions by replacing the on-site diesel generator with more sustainable sources.

1 Power distribution architectures

1.1 AC power distribution

Data centers are typically fed from one, or more, alternating current (AC) power sources/feeds and implement an AC power distribution architecture to distribute the power to the various loads, such as the network infrastructure, its cooling and supporting infrastructure, as shown in Figure 2.

Power processing is performed at various intermittent stages during the distribution to convert the high voltage AC into a stable, low voltage DC suitable for loads such as microprocessors. Uninterruptible power supplies (UPS) perform the required power conditioning and charge the backup battery bank, which compensates for fluctuations from the grid or temporary power loss together with the on-site diesel generator.

The reliability of the power supply is sought in redundancy of the AC feeds from the public grid, UPS power conditioning as well as on-site power generation, typically from a diesel generator.

The cooling infrastructure is more tolerant of unconditioned power, but reliability and redundancy considerations usually decide the ultimate power delivery paths to these equipments. Additionally, even though uninterrupted cooling to the racks is required, the computer room air conditioners can still be treated as a non-critical load to enable reduction of power delivery costs. Instead, to compensate for the downtime between a power failure and start-up of the generator, a chilled water storage tank can be used with the circulation pump being treated as a critical load, according to [8].

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[4] Processor inefficiencies (consuming 70 watts to 90 watts on average, some as much as 150 watts) reached critical mass when silicon chips migrated to 90 nm technology, according to [7], as the leakage current for transistors then became a meaningful part of the overall power consumption.

[5] Efficiencies can be as low as 50% at light load conditions [4]

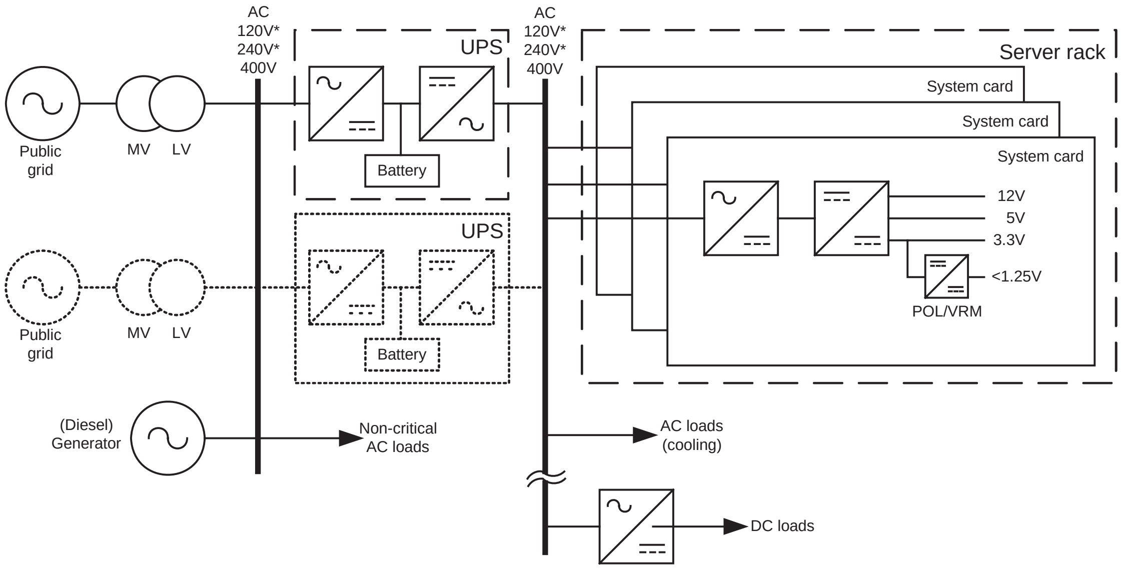


Figure 2 Typical AC distribution architecture (dotted components are optional)

Both the incoming bus and the internal distribution bus are AC with a common voltage level of approx. 400 V_{rms} in Europe and 120 V_{rms} or 240 V_{rms} in the United States, for example [4].

There are no less than three sequential power conversion stages involving a change from AC to DC or vice versa required for a single system card in the network using the AC distribution architecture, as depicted in Figure 2. This wastes energy, which is emitted as heat and increases the need for cooling. It would be far more efficient to power servers directly from a central DC supply [5].

1.2 DC power distribution

The application of DC distribution architecture has been suggested as an efficient method of power delivery within a data center. This concept is inspired by the absence of reactive power, the possibility of efficient integration of small, distributed generation units, e.g. photovoltaic arrays and fuel cells, and the fact that, internally, all the loads operate using a low DC voltage [9].

Transformers make it easily possible to increase an AC voltage, allowing power to be transmitted via cables over great distances with very little loss. With a DC voltage, this is not easy to achieve and there are major losses during transport [10]. However, great advances have been made in DC technology, especially in the low (< 50 V) and industrial voltage range (up to 1000 V). Voltages can now be easily regulated with compact integrated electronic circuits, and power electronics for direct current make the efficient and accurate control of electrical power possible [10]. Furthermore, energy transport in a data center is confined to the extremities of the facility itself (< 100 m), making transport losses less critical.

The feasibility of DC power distribution has already received some attention in the literature regarding low and medium voltage power systems [11], commercial and residential facilities [12] as well as ultra-low voltage (48 V) DC networks for domestic application [9]. In summary they conclude that if the semiconductor losses in converters are considerably reduced, the total system losses are decreased when DC is used and that the DC system leads to a better utilization of the high voltage/medium voltage transformers, allowing an increase in demand without changing the transformer [9]. An optimal voltage level could be 326 V (the peak value of the voltage of the utility grid in Europe) and that DC distribution is infeasible if large loads have to be fed [9].

Changing from an AC power distribution architecture, as shown in Figure 2, to a DC power distribution architecture, as shown in Figure 3, replaces the AC distribution bus with an equivalent DC distribution bus, removing two of the three sequential AC-DC/DC-AC power conversion stages.

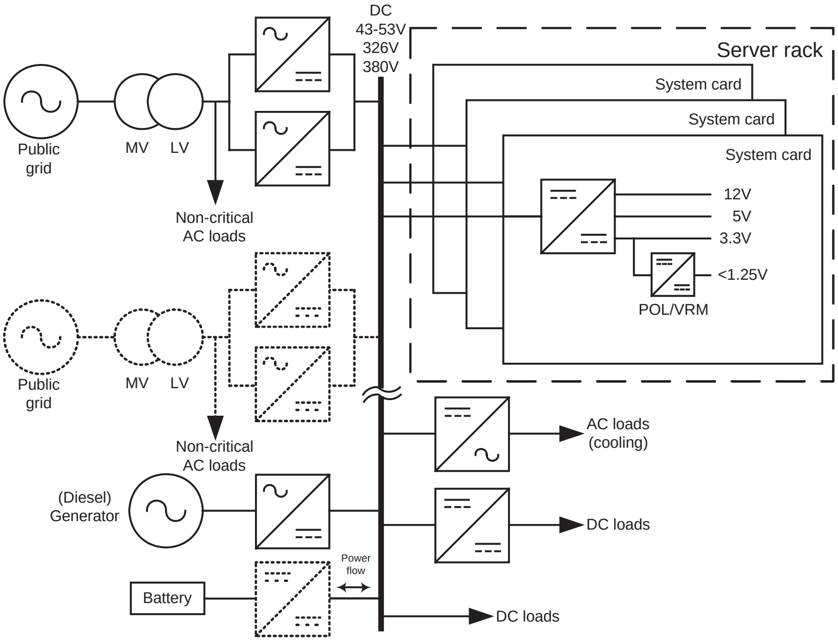


Figure 3 Typical DC distribution architecture (dotted components are optional)

Redundancy is still provided by a secondary AC feed, but now also includes a parallel AC-DC converter to feed the DC distribution bus as well as an AC-DC converter to connect the on-site power supply (diesel generator) to the DC system.

Only a single power conversion stage involving a change from AC to DC or vice versa is now required to power the system cards in the network. For AC loads, such as the cooling of an additional DC-AC inverter is required, increasing the number of power conversion stages to two for this load. This is similar to the AC distribution system.

The DC bus voltage level varies according to the amount of energy required by the data center. To yield a given amount of supplied power, the current must be increased when the voltage is lowered. Thus supplying power at lower voltages generates more heat, which wastes some of the power that could be used by servers. For larger data centers, a higher distribution voltage is chosen to reduce the transmission losses in the copper conductors, typically to the value of rectified AC: approx. 326 V. Implementing a 48 V DC bus, as is commonly used in telecommunications facilities, would require bulky conductors. It is therefore impractical to distribute DC power to large loads at 48 V but this problem can be overcome by increasing the distribution voltage to 480 V and stepping it down on the server cards to lower values (43 – 53 V) on an intermediate DC bus [13]. This intermediate DC bus can be used to reduce the transformation ratio between the DC bus voltage and the final voltage required by the microprocessor load. Furthermore, to ensure that the microprocessor loads are provided with a precise regulated voltage, an intermediate bus can be implemented to reach the critical tolerances on the output voltage and this allows some leeway on the voltage of the DC distribution bus. The higher voltage DC bus can then be used for energy transport over longer distances and to power larger loads as well. A DC distribution architecture including an intermediate DC bus is shown in Figure 4. The point-of-load (POL), or voltage regulation modules (VRM) are DC-DC converters that regulate the respective output voltages to the required tolerance without providing galvanic isolation.

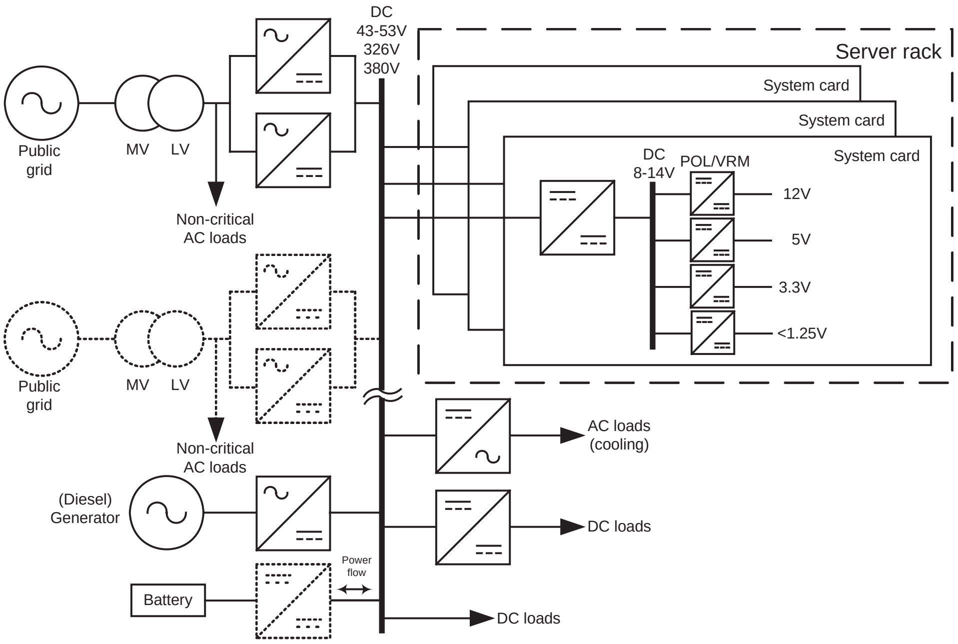


Figure 4 DC distribution architecture with intermediate bus (dotted components are optional)

2 Reliability

It was emphasized in the introduction that the reliability of the power supply and distribution is crucial in data centers, and therefore the distribution system is made redundant. This redundancy in the power distribution is necessary for creating an alternative (parallel) path for power to reach the load if some component(s) should unexpectedly fail.

In both AC and DC distribution, the reliability of the power supply is sought in redundancy of the AC feeds from the public grid, UPS power conditioning as well as on-site power generation, typically from a diesel generator. For DC distribution, the battery connected to the DC bus replaces the UPS used in the AC distribution architecture. More on-site power generation and storage capabilities will be addressed later in this paper.

In any current flow path the component with the lowest mean time between failure (MTBF) rating determines the overall reliability of that path. The more components there are in the current flow path, the higher the risk becomes of that path failing. The main current flow path in a data center consists only of power conversion equipment, one AC transformer and thereafter only power electronic converters. Power converters have, due to their sophisticated nature (high operating frequency and demanding component stresses), a relatively low MTBF, in the order of 10 - 20 years. Reducing the number of power converters in a data center's critical current path will therefore drastically increase the MTBF and thereby its reliability. This especially holds for AC-DC converters, as AC-DC converters are more complex than DC-DC converters from the point of view of their structure and, if they are of the forced commutation type, the control system is also very prone to failure [14].

A comparison between these aspects of AC and DC distribution regard follows. The DC distribution architecture, shown in Figure 3, has the least power converters in its crucial path: two (1x AC-DC, 1x DC-DC) compared to four (2x AC-DC, 1x DC-AC, 1x DC-DC) in the AC distribution architecture, shown in Figure 2, excluding the POL/VRM. In this regard the reliability of the DC distribution architecture will be higher than that of the AC distribution architecture, with a MTBF in the order of 50 - 80 years.

Reducing the number of power conversions to single point of conversion increases the vulnerability of the system, therefore the number of power conversion stages in a current flow path should be reduced, but parallel flow paths (redundancy) should also be introduced to compensate for the reliability of the overall power supply. Such a full redundancy increases the MTBF of a DC distribution system to 400 years or more, according to Cluse [1].

3 Efficiency

To comment on the efficiency of a specific distribution architecture, the power distribution and its losses need to be considered. The following example illustrates the approach.

In a typical data center implementing AC distribution, as shown in Figure 2, the incoming electrical power is distributed as shown in Figure 5 and leaves the system primarily as heat.

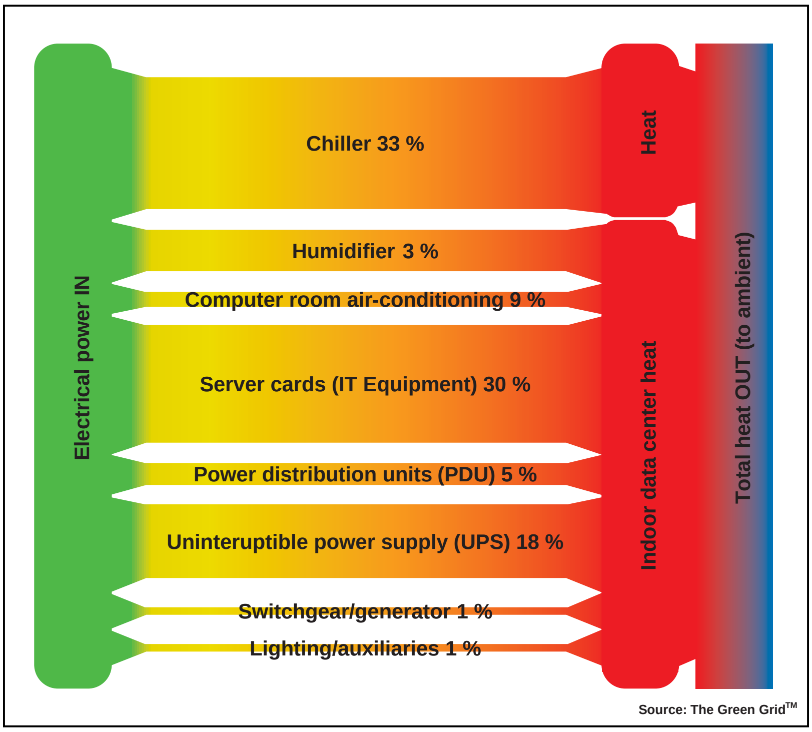


Figure 5 Power distribution within a typical data center implementing AC power distribution [15]

The power consumed by the UPS is primarily to compensate for the losses in the two conversion stages, first from AC to DC and then from DC back to AC. These losses are assumed to be distributed equally between the two UPS power electronic converters, resulting in approx. 9% per converter.

A typical server card (dual processor) consumes approx. 450 W of power, distributed amongst its peripherals as shown in Figure 6. It can be seen that approx. 160 W (35%) are losses in the power conversion process, according to [6].

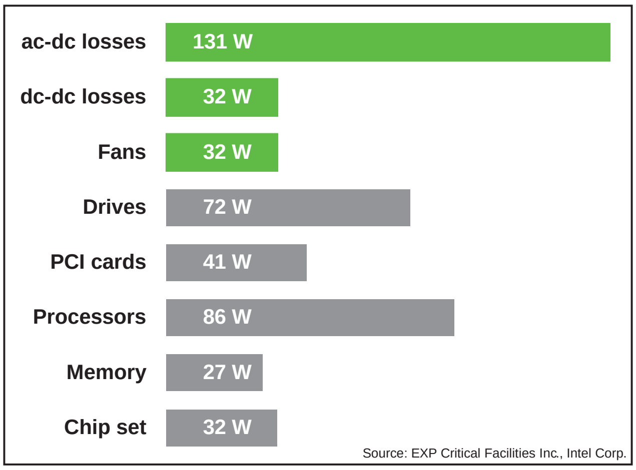


Figure 6 Power distribution for a typical server card (dual processor) consuming approx. 450 W.

From the above loss analysis it can be seen that a DC distribution architecture already saves 131 W (29% of the server card losses) by removing the AC-DC conversion on the power card itself. This amounts to an 8% saving in the overall data center losses. A further 9% reduction in overall data center losses is achieved by removing one of the two UPS converters. A DC distribution architecture therefore saves 17% of the overall losses of a data center.

In the literature, various institutions predict similar savings in overall data center losses to those indicated in the above example. Researchers at the Lawrence Berkeley National Laboratory in the USA have experimented with a DC distribution architecture, as shown in Figure 3, with a DC bus at 380 V. They concluded that the elimination of inefficiencies caused by having to convert between DC and AC reduced the overall data center power loss by 10 to 15% [4]. Calculations by Engelen et al. [9] show that a reduction of approx. 20% in electricity charges could be expected when an Internet data center with an AC distribution bus at 100 to 200 V migrates to a DC distribution system. The saving is due to the same reason as above. An American company 'Industrial Light & Magic' reports savings from 10 to 20% since their migration from AC distribution, with an AC bus at 480 V, to DC distribution for their server cards, with a DC bus at 48 V [16]. Yet again due to the same elimination of inefficiencies as above.

A central AC-DC converter feeding the DC bus in a DC distribution architecture is more efficient than several smaller AC-DC converters in each server rack [16]. The amount of 'electronic overhead' (losses due to control and auxiliaries within the converter) is much less in such a larger converter. A single point conversion however reduces the reliability of such a system, necessitating a redundant implementation, as discussed earlier.

Another advantage of DC distribution is the lack of reactive power in the system. Reactive power results in increased losses in AC systems due to larger current magnitude for an equal amount of transferred power. Non-linear loads, such as AC-DC converters (without power factor correction (PFC)), require reactive power in an AC system. In view of the large number of converters in data centers, much is to be gained by migrating to a DC system.

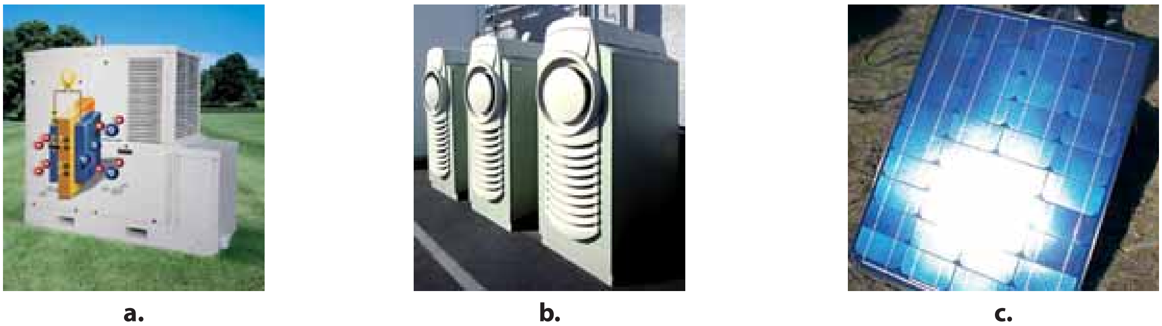
A key parameter in the efficiency in a data center is the light load efficiency, as this is usually far worse than the efficiency at the rated load. This parameter is however independent of the choice of distribution architecture and therefore not addressed in detail in this paper.

A further advantage of DC distribution is that it facilitates the implementation of sustainable energy sources as well as energy storage. This is discussed in the next section.

4 Promising emerging technologies for supporting DC power distribution

Different techniques can be used for on-site power generation in data centers, which can eliminate dependence on grid power or be used for backup power in situations where the grid power is expensive or unreliable. On-site power production is most commonly achieved via diesel generators, as illustrated in both Figure 2 and Figure 3 [5], [8], but alternative sustainable technologies, delivering significant advantages in terms of reduced emissions, reduced noise levels and reduced fuel dependency are already available and could be of interest to data centers as well.

Modern distributed generation technologies provide various topologies of small size generators, in the order of tens of kW, that generate – from sustainable energy sources – DC directly (photovoltaic arrays and fuel cells) or require a DC intermediate conversion stage for transforming the high frequency electrical energy into suitable AC energy (micro-turbines, Stirling engines, micro-hydro turbines, variable speed wind generators) [10],[14]. Figure 7 shows some examples.



a. b. c.

Figure 7 Generation technologies from sustainable energy sources that could provide on-site power support for data centers, (a) static fuel cells, (b) micro-turbines and (c) photovoltaic cells

Most of the electrical storage systems, such as osmosis batteries, super capacitors and superconducting magnetic energy storage (SMES), supply DC electrical energy. Others, like flywheels, generate high frequency currents that must be converted into DC, or implement a DC intermediate conversion stage for AC connection [14], [17]. Figure 8 shows some examples.

a. **b.** **c.**

Figure 8 Energy storage technologies that could provide on-site power support for data centers, (a) super capacitors, (b) high speed flywheel and (c) osmosis battery stack

Including all the above mentioned on-site power generation and power storage equipment into the AC distribution architecture shown in Figure 2 requires six power conversion stages to connect the DC and high frequency AC sources to the AC bus, as shown in Figure 9. The DC-AC inverters then simultaneously perform the synchronization between the on-site generated power frequency (> 50/60 Hz) and the AC distribution power frequency (typically 50 or 60 Hz) [17].

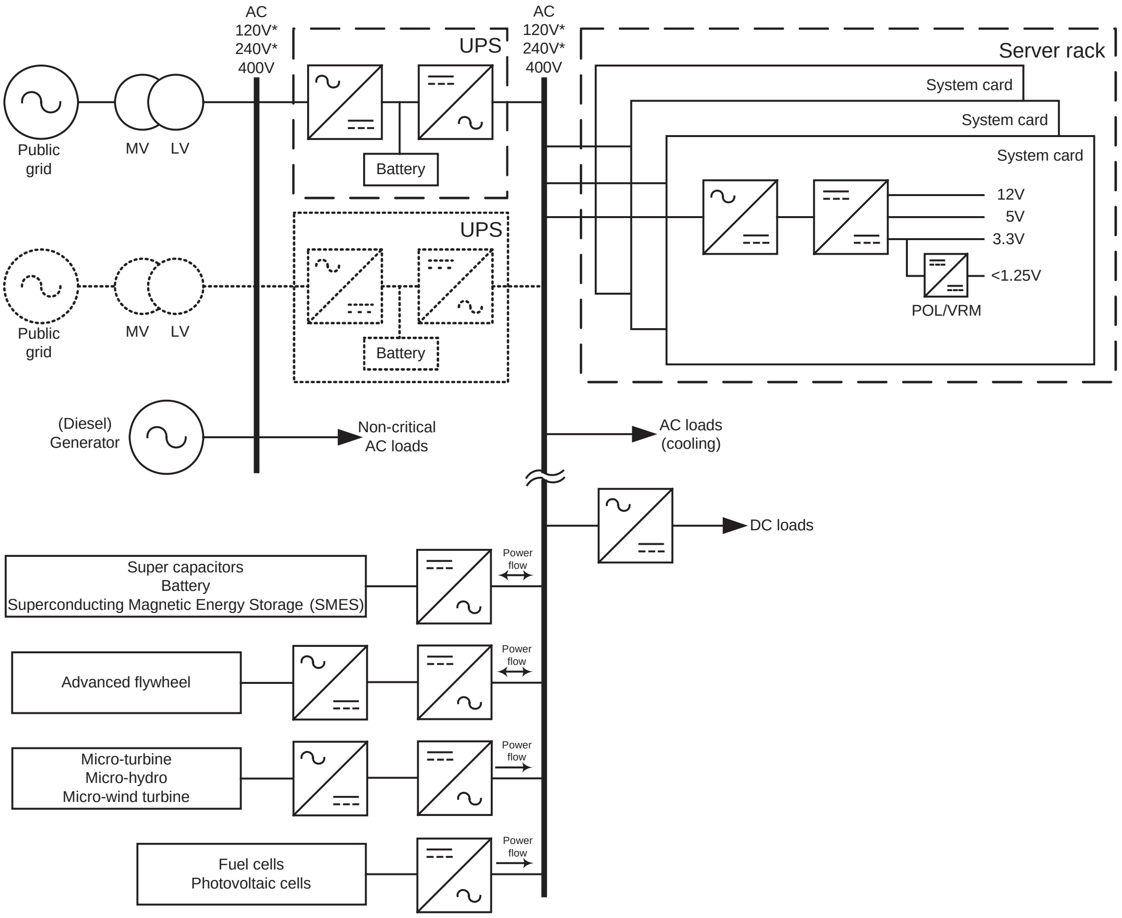


Figure 9 AC distribution architecture with DC support (storage & generation, dotted components are optional)

Similarly, connecting all these sources and storage components to the DC distribution architecture shown in Figure 3, requires only two power conversion stages, namely for the high frequency AC sources, as shown in Figure 10. Optionally, to benefit from advanced efficiencies and power control of the DC sources and storage elements, these could be connected to the DC bus using a DC-DC converter, as shown.

The connection of these sources and storage elements to a DC distribution bus does not require any synchronization between the DC power sources.

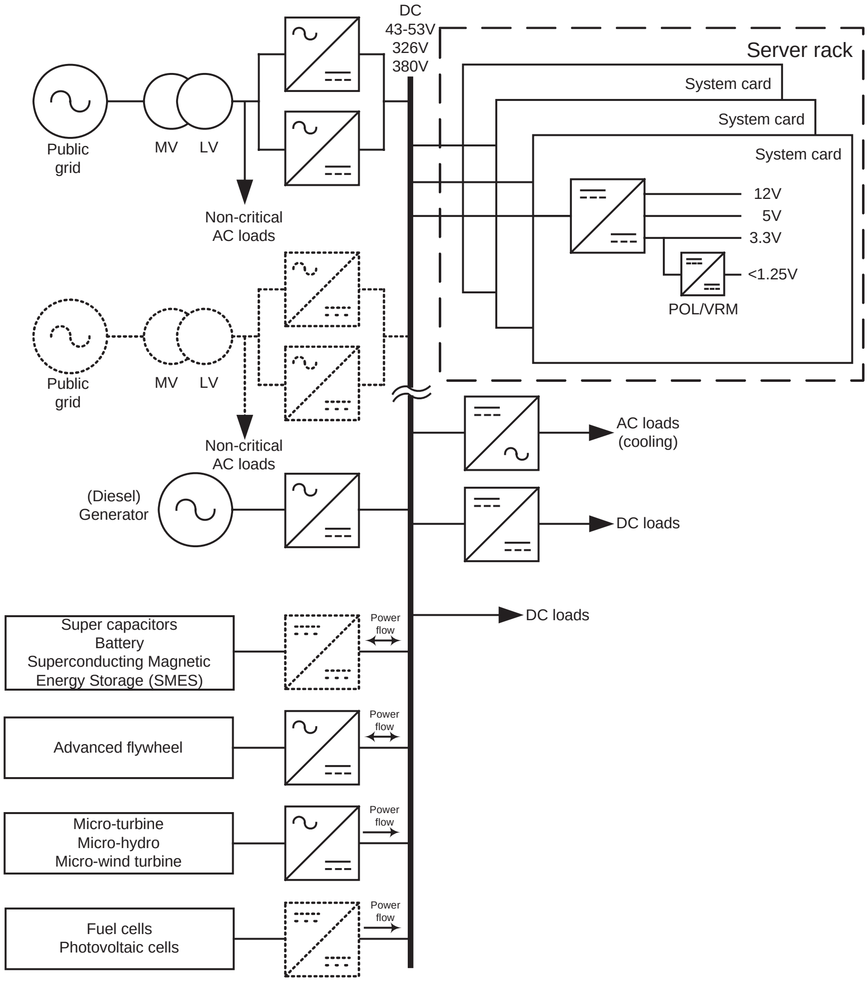


Figure 10 DC distribution architecture with DC support (storage & generation, dotted components are optional)

It can be seen that the reliability and efficiency of the overall data center power distribution will be higher in the DC distribution architecture due to the considerably lower number of power conversions, as discussed in previous sections of this paper.

As the technology for the on-site power generation and power storage improves and more capacity is installed within a data center, a point will be reached where the on-site generation matches, or exceeds, the energy demand of the data center. When this occurs the data center could become independent of the public supply grid and be controlled as a so-called microgrid, with DC being the obvious distribution architecture. In this case the public grid will then only serve as backup to the on-site power generation and on-site power quality can be controlled locally and very specifically.

Microgrids can be designed to meet the exact needs of a data center, such as enhancing local reliability, reducing losses, supporting local voltages, providing increased efficiency, implementing voltage sag correction and providing uninterruptible power supply functions, amongst others, according to Lasseter [18]. This is possible as the microgrid spans only the data center and all of its parameters can be controlled by the data center operator/owner. Kakigano et al. [19] reports that a DC microgrid enables superior high quality power supply, easy isolation of system faults, higher conversion efficiencies due to downsized, transformerless converters, amongst others. Although the technology needs to mature a bit further, self-sustaining microgrids could be providing power to data centers in the near future.

5 Status of DC distribution in industry

A few existing data center companies have already switched to a DC distribution architecture in one form or another and have reported their findings in the literature. One example is *Data393*, a data center company based in Denver, Colorado, USA, which has reported a reduction in power consumption of nearly 20% due to the change to DC distribution [5].

Bill Tschudi [4], a principal investigator at the *Lawrence Berkeley National Laboratory*, reported that researchers there have experimented with transmitting power at 380 V DC within the data center, which reduced power loss by 10 to 15%. He goes on to say that switching to a DC distribution architecture would not only reduce heat-based energy losses but would also eliminate inefficiencies caused by having to convert AC coming from the electrical grid into DC, as discussed in a previous section as well.

Peter Gross, CEO of consulting engineering firm *EYP Mission Critical Facilities Inc.* reported savings from 10 to 20% by changing to a DC distribution architecture and then being able to effectively replace the AC-DC power converters, with a typical efficiency of 65%, with DC-DC converters with efficiencies in excess of 90% [16].

Looking beyond data centers, it can be seen that other industries have also benefited from a change to DC power distribution: DC voltage has already been used with success for high voltage DC transmission, shipboard systems, traction systems and communication networks [17].

DC distribution has been adopted in applications where reliability is of great importance, such as in propulsion and shipboard systems for marine application. Baran et al. [20] states that the new solid-state power electronics-based converters employed in the new DC distribution systems (within naval vessels) help overcome two of the main challenges associated with DC systems: reliable conversion from AC-DC or DC-AC, and interruption of DC current under both normal and fault conditions.

In other braches of the transport industry it is also expected that automobile power configurations will be designed as distributed DC power systems.

The data center industry closely resembles the telecommunication industry, seeing that the first has almost been spawned from the latter. The telecommunication industry has, in response to the required reliability, pursued DC distribution in preference to AC distribution.

Practical impediments regarding DC distribution in data centers

One problem that is currently keeping DC power distribution from widespread implementation is that there is no single standard for DC power supplies. Data centers cannot easily achieve savings due to a standardized voltage level if the data center is filled with equipment from different vendors [5]. Developing new power supply standards is mandatory in order to solve this situation. Internationally, agreements will have to be made about the DC voltage level. This is necessary to ensure that various countries do not select different voltage levels, which would prevent the establishment of an international standard for equipment and would lead to the need for a whole new range of power supplies and power converters [10].

The migration from an existing AC distribution architecture in a data center to a DC distribution architecture is a steep investment and might not outweigh its financial benefits. However, the increase in reliability might be the decisive factor. In the development of new data centers this impediment does not exist and therefore a DC distribution would be a more attractive option in the long run.

6 Conclusions

In conclusion, a comparison of all the aspects of AC and DC power distribution within a data center application, which have been addressed in this paper, is presented in Table 2.

From Table 2, it can be concluded that the reliability and efficiency of a typical power distribution architecture can be improved simultaneously by decreasing the number of required power conversions within the crucial current path from the source (public grid or on-site power generation) to the load (server card with its microprocessor). Care has to be taken to avoid all the power having to pass through a single point of conversion as this will have an adverse effect on the reliability of the overall power distribution system, making it more vulnerable to failure. Implementing a redundant distribution architecture solves this vulnerability.

Considering the discussions on reliability and efficiency presented in this paper and regarding the differences between AC power distribution and DC power distribution, it can be concluded that a DC power distribution architecture holds the most advantage regarding reliability (measured in MTBF) and efficiency as it only requires two (2) power conversions, as opposed to four (4) for an AC power distribution architecture. Efficiency improvements ranging from 10 to 20% have been reported in the literature for data centers previously using an AC power distribution architecture that have adopted a DC power distribution architecture.

Furthermore, it can be concluded that DC power distribution holds the most advantage for the connection of emerging technologies for on-site power generation and energy storage as a significant amount of this equipment delivers power in the form of DC or alternatively as high frequency AC, which then requires an intermittent DC conversion. Having a suitable DC bus available in the distribution architecture saves at least one power conversion, and its associated losses and chance of failure.

Aspect	**AC distribution**	**DC distribution**	**Affect on reliability**	**Affect on efficiency**
Minimum number of power conversions required	Four	Two	Reliability increases with a reduction of power conversions	Efficiency increases with a reduction of power conversions
Number of power conversions required for UPS functionality	Two	One	Reliability increases with a reduction of power conversions	Efficiency increases with a reduction of power conversions
Power conversion performed by	AC transformer and power electronic converters	Power electronic converters	AC transformers are more reliable than power electronic converters	Similar efficiencies for AC transformers and modern power electronic converters
Frequency at which power conversion is processed	Grid frequency (50 / 60 Hz)	High switching frequencies (> 100 kHz)	Converters with higher switching frequencies are more susceptible to failure, reducing its reliability	Higher switching frequencies increases power converters efficiency (and power density)
Synchronization required when connecting on-site generation or storage	Yes, for all loads	No, all loads attached to DC bus	Reliability increases if no synchronization is required (lower risk of inadvertent failure)	Efficiency not affected by synchronization
Conversion required when connecting on-site generation or storage	Always	Only for high-frequency AC equipment	Reliability increases with a reduction of power conversions	Efficiency increases with a reduction of power conversions
Redundancy possible	Yes	Yes	Redundancy significantly increases the reliability	Redundancy does not effect efficiency

Table 2 Comparison of aspects, concerning reliability, efficiency and ability to connect emerging technologies to support on-site power generation and energy storage, between AC and DC power distribution

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