Qualitative Analysis of Power Distribution Configurations for Data Centers

White Paper #4

Executive Summary

Many different power distribution configurations exist today that can be used to power a data center. Each of these configurations has its own advantages and disadvantages that can have a major impact on all aspects of the facility. This paper discusses the qualitative differences between seven possible configurations that can either be found in the United States or Canada today, or could be used in the future.

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Introduction

This paper will examine a variety of power distribution configurations for data center applications and compare the advantages, disadvantages and the future outlook of each configuration. The emphasis for the analysis will be on energy efficiency. The discussion here is strictly qualitative; any quantitative discussion is beyond the scope of this document. For this paper, alternating current is abbreviated "AC", direct current is abbreviated "DC" and volts is abbreviated "V".

The power distribution configurations discussed are:

1) 480V AC
2) 600V AC
3) 277V AC
4) 400V AC
5) 48V DC
6) 550V DC
7) 380V DC

The advantages and disadvantages of each of the following attributes are discussed for the power distribution configurations:

- Current usage and availability
- Efficiency
- Reliability
- Equipment
- Standardization and acceptance

Background and Assumptions

The power distribution configurations are described based on what is needed to build a new data center in the United States or Canada with 480V AC or 600V AC input at the building service entrance. It focuses on the power delivery path to the compute equipment and does not include powering of other loads, e.g. the cooling plant. This paper will analyze a single power path. Many data centers utilize parallel, redundant power paths to achieve higher availability which mitigates the effect of single failure points, improving the availability of the system.

The specific voltage used for each configuration is merely a nominal voltage that was chosen for the analysis purposes of this paper. The specific voltages are representative of the possible ranges that could be used; for example, configuration 6 (550V DC) could theoretically range anywhere from 500-600V DC.

In general, fewer conversions within a configuration will inherently result in a higher efficiency. This higher efficiency will result in electrical cost savings and will reduce cooling requirements. Based on published efficiency data and assuming best in class components are used, at 30 percent and higher loading, efficiencies of the various configurations are within 5-10 percent of each other.

Alternative energy sources can be connected with any system. Alternative energy sources are DC and would generally be easier to integrate into a DC system. Any alternative energy source could be used to reduce the overall load on either an AC or DC configuration. For the purposes of this paper, it is assumed that a facility will generate far less power than it consumes, resulting in no net power flow back to the grid. The following is a brief description of each of the equipment types in the distribution path:

Building Entrance

The building entrance, also called a service entrance, is the boundary between the data center's electrical system and the utility grid. It is the origin for each of the configurations discussed.

Input Switchgear and Distribution

This encompasses all equipment needed to provide the proper electrical protection for the data center per the National Electric Code (NEC).

UPS

The typical uninterruptible power supply (UPS) in an AC system uses a double conversion topology that will rectify the input power from AC to DC and invert back to AC output again. The UPS contains batteries that can supply power via the inverter to the load when utility power is unavailable. This study will also briefly discuss alternate UPS technologies for certain configurations. Any equipment labeled "DC UPS/Rectifier" will have an AC voltage as an input, contain batteries and then output a DC voltage; the AC inversion will not take place. In a redundant UPS system, multiple power paths are possible. For simplicity, only the 3 phase line to line voltage is listed until the rack input.

Static Transfer Switch

A static transfer switch is a solid state device used by UPS systems to transfer loads between two independent AC power sources.

Transformers/PDU

Isolation transformers and power distribution units (PDUs) are often integrated as a single unit in many data centers and this approach is used for this analysis. A typical PDU in an AC distribution configuration contains an isolation transformer to step the AC distribution voltage down to the desired voltage. The other main function of a PDU is to house circuit breakers that are used to create multiple branch circuits from a single feeder circuit. These branch circuits then supply power to the IT equipment throughout the data center. Because PDUs are generally rated at a small fraction of the UPS's rating, a data center typically has numerous PDUs. Note that for simplicity, only one PDU is shown in each figure.

Autotransformer

Because it does not supply isolation and because it has a single winding, an autotransformer is much smaller, lighter, cheaper and more efficient than a typical isolation transformer.

DC/DC Converter

The converter essentially does the DC work equivalent to a transformer, stepping the DC voltage down or up.

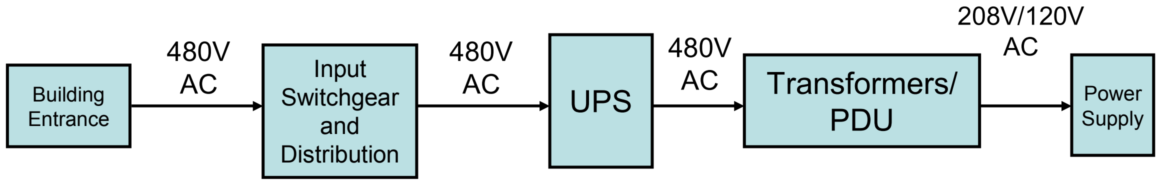
Power Supply

For the purposes of this analysis, it is assumed that the output voltage of all power supplies is 12V.

Distribution Configuration Analysis

The distribution analysis of 480V AC, 600V AC, 277V AC, 400V AC, 48V DC, 550V DC and 380V DC begins below.

Distribution Configuration 1: 480V AC



Highlights:

- This is the most common configuration in use in the United States (US) today and will be the basis for all other comparisons.

Table 1 - 480V AC Configuration Advantages and Disadvantages

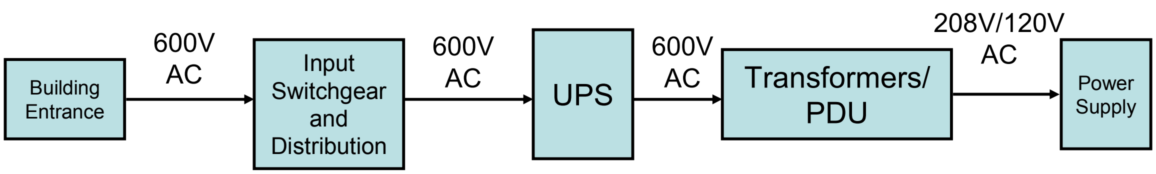
	Advantages	Disadvantages
Current usage and availability	This configuration is very common and usage is widespread. All system components are available off the shelf.	Historically, this configuration has not often been optimized for efficiency.
Efficiency	High efficiency equipment is becoming more and more available throughout the industry.	Multiple power conversion stages between AC and DC voltages give inherent inefficiencies in the system. Because the load cannot directly utilize the distribution voltage, this configuration requires numerous isolation transformers resulting in added losses and lower efficiency. High efficiency equipment can be more expensive than "typical" efficiency equipment.

	Advantages	Disadvantages
Reliability	Extensive knowledge in the industry has created the highly reliable and serviceable configuration, which has been proven to meet reliability objectives.	Many components and higher complexity than other configurations give a higher possibility of failures. Incremental increases in reliability by adding additional equipment, such as static switches or parallel UPS systems, can be very expensive.
Equipment	Because of high volumes, equipment such as PDUs, UPSs or AC circuit breakers are common, widely available and relatively low cost.	The number and relative size of the components in this configuration requires more floor space. Paralleling AC UPSs is more complex than paralleling DC UPSs. Transformer/PDU take up space, add to weight on the raised floor and add heat load.
Standardization and acceptance	There are many standards already in place for this configuration. It is accepted and known by many groups involved with the data center, including but not limited to users, consulting engineers, inspectors, architects and electrical contractors.	

Future outlook:

Because it is so commonly used, this distribution is likely to be used well into the future. Many equipment manufactures are striving to increase efficiencies on their products and educate consumers on ways to use their products as efficiently as possible.

Distribution Configuration 2: 600V AC



Highlights:

- This configuration is currently used by most Canadian data centers.
- There are several sites in the United States that have been using this system for many years.

Table 2 - 600V AC Configuration Advantages and Disadvantages

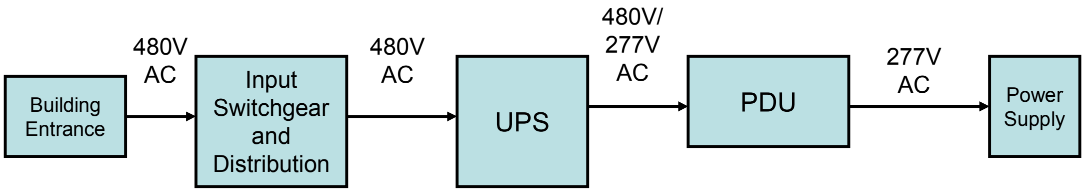
	Advantages	Disadvantages
Current usage and availability	This configuration is possible in the US without any major changes to infrastructure.	This configuration is not commonly used in the US.
Efficiency		Multiple power conversion stages between AC and DC voltages give inherent inefficiencies in the system. Because the load cannot directly utilize the distribution voltage, this configuration requires numerous isolation transformers resulting added losses and lower efficiency. High efficiency equipment can be more expensive than "typical" efficiency equipment. Some vendors create 600V AC UPSs by utilizing isolation transformers in conjunction with a 480V AC UPS. When this is the case, UPS efficiency is significantly reduced.
Reliability	This configuration has been proven reliable in field use.	This configuration has the same number of components as configuration 1 and will give the same probability of failures.

	Advantages	Disadvantages
Equipment	Nearly all, if not every, manufacturer already makes equipment for this distribution. 600V AC will be slightly less cost than configuration 1 because smaller amounts of copper are needed. Allows building of larger data center while using common 4000 amp distribution equipment.	The equipment is less common and has smaller install base. Paralleling AC UPSs is more complex than paralleling DC UPSs.
Standardization and acceptance	No additional product safety regulations would be needed for 600V in the United States.	

Future outlook:

Because 600V AC is not readily available for US electrical distribution systems and because higher efficiency alternatives exist, it is unlikely that this system will ever become popular in the US.

Distribution Configuration 3: 277V AC



Highlights:

- This is the US version of a 400V/230V AC configuration.

Table 3 - 277V AC Configuration Advantages and Disadvantages

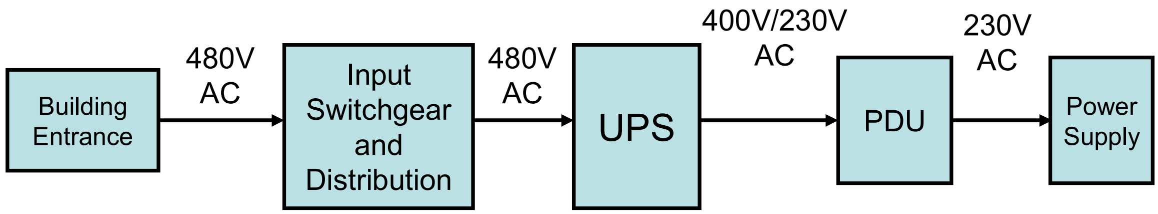
	Advantages	Disadvantages
Current usage and availability		This configuration is not common in data centers.
Efficiency	System efficiency should be higher than for configuration 1 because of elimination of the isolation transformers in the numerous PDUs. High efficiency equipment is becoming more and more available throughout the industry. There is an increase in efficiency when running IT equipment at 277V AC versus 208/120V AC.	High efficiency equipment can be more expensive than "typical" efficiency equipment.
Reliability		Incremental increases in reliability by adding additional equipment, such as static switches or parallel UPS systems, can be very expensive.

	Advantages	Disadvantages
Equipment	No transformer is needed in this configuration. This configuration reduces wire size. At high volumes, the cost of 277V AC power supplies should be comparable to standard AC equivalents.	Very little high volume equipment available to run on 277V AC, which reduces purchasing options and increases cost. Because most connectors and breakers are only rated to 250V AC, very limited computing equipment is available that can run on 277V AC. Paralleling AC UPSs is more complex than paralleling DC UPSs.
Standardization and acceptance	The current US standards already include the voltages in this configuration. Many consulting engineers and contractors are familiar with this system.	Because 277V AC is above the 250V AC rating of nearly all IT equipment, a new standard similar to that used in 277V emergency lighting would need to be adopted within the IT industry.

Future outlook:

Because 277V AC is above the 250V AC rating of nearly all IT equipment, changes would have to be implemented in the power supplies of IT equipment for this system to become practical. Higher voltage rating connectors and breakers will also be required. Because of these required changes, 277V AC systems may be less prevalent than 400V AC systems in the near term. It is believed that potential efficiency gains are comparable to other architectures. If this proves to be the case, 277V AC may become more of a mainstream offering in the future.

Distribution Configuration 4: 400V AC



Highlights:

- This system is a hybrid approach that brings most of the efficiency and all of the equipment compatibility advantages of the end-to-end 400V AC systems commonly used in the rest of the world, to the US, in a manner that is simple to retrofit into an existing 480V AC environment or deploy in a new 480V AC data center
- With the correct transformer at the service entrance, this system could also be built as an end to end 400V AC system,

Table 4 - 400V AC Configuration Advantages and Disadvantages

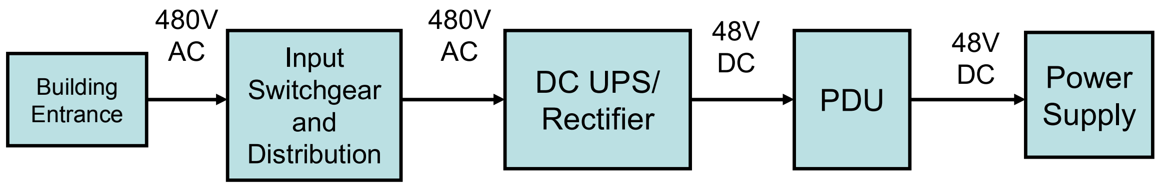
	Advantages	Disadvantages
Current usage and availability		This setup is not very widespread in the United States, but it is very common outside of North America.
Efficiency	System efficiency should be higher than configuration 1 because of elimination of the isolation transformers in the numerous PDUs. There is an increase in efficiency when running IT equipment at 230V AC versus 208/120V AC.	

	Advantages	Disadvantages
Reliability	Reliability for this configuration is comparable to or slightly better than the 208/120V AC distribution, because it has fewer components.	
Equipment	AC power is taken directly to the rack power supply without an additional isolation transformer. All power equipment is readily available today. Computing equipment needs no changes to run from 230V AC. Configuration would be less costly than the 208/120V AC system because of the elimination of multiple isolation transformers and smaller branch circuit conductors.	Need an autotransformer in the bypass path of the UPS. Paralleling AC UPSs is more complex than paralleling DC UPSs.
Standardization and acceptance	All US standards already apply to this configuration.	Unfamiliarly with the system may cause confusion with local building authorities.

Future outlook:

Because this configuration is more efficient, more reliable and less costly than configuration 1, as well as being readily deployable, it could be expected to be widely used in the coming years.

Distribution Configuration 5: 48V DC



Highlights:

- This configuration has existed for many years in the worldwide telecommunications market and is very well understood in that industry. Due to its negative polarity, it is sometimes known as -48V DC.

Table 5 - 48V DC Configuration Advantages and Disadvantages

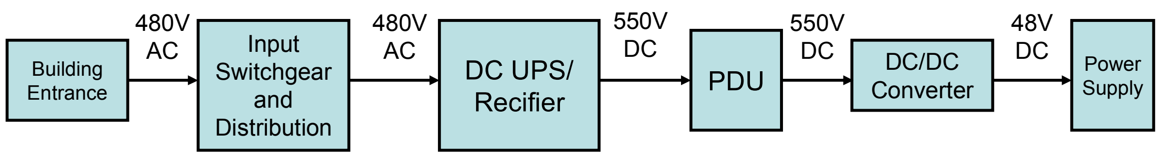
	Advantages	Disadvantages
Current usage and availability	This system is well known and widely used in the US telecom industry, as well as in several smaller data centers.	This system is not very widely used in large data centers.
Efficiency	The configuration should give a higher efficiency than configuration 1 because one or more conversion stages are eliminated.	In extremely large plants, there is a requirement for large copper runs; it requires “distributed” infrastructure versus a centralized infrastructure.
Reliability	The system has proven to be very reliable in the telecom industry. Static switches at the UPS output are eliminated, reducing reliability concerns about static switch failure.	

	Advantages	Disadvantages
Equipment	Equipment for a 48V DC configuration is widely available. DC power plants are generally smaller than comparable AC power plants because they have fewer conversion stages. The voltage used in this configuration is suitable for direct backplane distribution; therefore it has the potential to eliminate chassis level power supplies. Paralleling DC UPSs is less complex than paralleling AC UPSs; therefore the system can more easily be scaled with varying data center capacity.	Larger gauge power cables and/or bus bars are needed to keep distribution losses low, increasing cabling costs. This may make the solution impractical for large, centralized, high density data centers. In a distributed system, many rectifiers and battery strings are needed for this setup to keep the low voltage transport distance as short as possible. This configuration is better suited to an environment where rectifiers can have shorter cable runs to the equipment than with long cable runs from a power room at one end of a very large facility.
Standardization and acceptance	There are worldwide standards already in place for this distribution. Safety and grounding practices are well understood. 48V DC is considered a Separated Extra Low Voltage (SELV), though it can still present an energy hazard.	There is a lot of expertise in the telecom industry with this configuration; however it is not as familiar to data center operators.

Future outlook:

This is a common configuration in the telecom industry. This high efficiency configuration, which eliminates some of the intermediate conversions common in most AC systems, is available for data centers today. Concerns over the use of larger gauge cables or bus bars may be mitigated by using distributed DC systems over shorter distances. However, 48 V DC distributions may be impractical for large, centralized, high density data centers.

Distribution Configuration 6: 550V DC



Highlights:

- While this configuration concept may be new when applied to the design of data centers, 500-600V DC is used in several other areas such as renewable energy generation and transportation markets.
- From a standards and safety viewpoint (UL and ANSI), 550V DC is low voltage, even though 550V DC is often referred to as high voltage.

Table 6 – 550V DC Configuration Advantages and Disadvantages

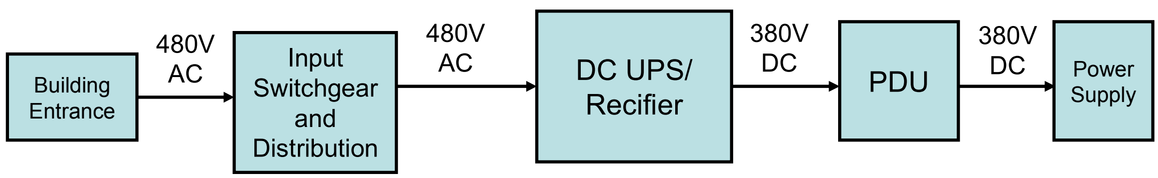
	Advantages	Disadvantages
Current usage and availability		This system is not widely used today.
Efficiency	When using today's products, this configuration should be more efficient than some of the 480V AC configurations.	This configuration should be less efficient than a 380V DC distribution because of the extra DC/DC conversion step.
Reliability	This configuration has fewer components as a whole when compared to configuration 1, which makes this inherently more reliable. With this configuration, static switches are not needed.	

	Advantages	Disadvantages
Equipment	This configuration reduces the size of the main distribution buses compared to 48V DC, making it comparable to 480V AC, and allows long distances between the power room and IT equipment. 48V DC input power supplies are available today Paralleling DC UPSs is less complex than paralleling AC UPSs.	Multiple converters are needed to keep transporting voltages high, varying from one per row to one per rack Only limited commercial rectifiers designed for this application available for today. Circuit breakers, fuses and hotplug circuits may be more expensive, are larger and have a more limited selection than AC rated equipment. Extra floor space and heat loading space are needed because of the multiple converters, when compared to other DC configurations. Current equipment is generally more expensive because of lower volumes.
Standardization and acceptance	The National Electrical Code, NFPA, UL and IEC cover the requirements for AC and DC voltages less than 600V in current specifications.	There is no standardization for other products affected by 550V DC power, such as connectors. There are no product safety standards or building electrical standards written specifically for 500-600V DC. Unfamiliarly with the system may cause confusion with local building authorities.

Future outlook:

This configuration shows promise as a means to provide higher efficiency and reliability than an AC system through the reduction in components. With facility level distribution at a high voltage and because standard 48V DC power supplies already exist, this configuration could be expected to find application in data centers in the future.

Distribution Configuration 7: 380V DC



Highlights:

- This is a relatively new configuration concept.

Table 7 - 380V DC Configuration Advantages and Disadvantages

	Advantages	Disadvantages
Current usage and availability	Similar DC voltages have been used successfully internal to several mainframe computer systems, but have not been commonly used for building distribution.	This system is not widely used in data centers today.
Efficiency	Fewer power conversion stages than configuration 1 should give a higher overall efficiency.	

	Advantages	Disadvantages
Reliability	This configuration has fewer components as a whole when compared to other systems, which should result in higher reliability. Static switches are not needed at the output of the UPS.	
Equipment	This configuration reduces the size of all distribution buses compared to 48V DC, making it comparable to 480V AC, and allows long distances between the power room and IT equipment. Generally DC conversion equipment will be smaller in size than AC equipment. The system can more easily be scaled with varying (capacity) size equipment. At high volumes, the cost of 380V DC UPSs and power supplies should be comparable to AC equivalents. Paralleling DC UPSs is less complex than paralleling AC UPSs.	380V DC compatible IT equipment is not available today because 380V DC power supplies have not been agency approved. However, 380V DC power supplies could easily be built. Only limited commercial rectifiers designed for this application are available today. Circuit breakers, connectors, fuses, inrush circuits and hotplug circuits may be more expensive, are larger and have a more limited selection than AC rated equipment.

	Advantages	Disadvantages
Standardization and acceptance	The National Electrical Code, NFPA, UL and IEC cover the requirements for AC and DC voltages less than 600V in current specifications.	A standard DC voltage into the rack has not yet been defined. A standardized connector needs to be established for the power supply input. There are no product safety standards or building electrical standards written specifically for 300-400V DC. Unfamiliarly with the system may cause confusion with local building authorities.

Future outlook:

There is a great deal of research being done on the 380V DC distribution system. While most of the equipment is not available for purchase today, the technology necessary is already available and it is likely that support equipment manufacturers could implement if the demand is there. The time it takes to implement is debatable. However, it will likely be a few years before 380V DC is a viable option for the typical data center because all power supplies for computing equipment would need to be modified, safety standards would need to be established, and electricians and end users would need to be trained.

Summary

The common existing and proposed data center power distribution configurations have been discussed. 480V AC and 600V AC are the standard data center alternating current power distribution systems in the USA and Canada respectively, the baseline or status quo for current data centers. They are expected to continue to experience only incremental efficiency improvements. 277V AC would offer an improved efficiency, however the changes to the power supplies in IT equipment and requirement for higher voltage breakers and connectors makes the system less likely to be become prevalent. 400V AC can be implemented today, is compatible with a wide variety of power distribution and IT equipment, and has the potential to increase system efficiency. 48V DC is the standard power distribution system for the telecom industry. It offers improved efficiency over common AC systems, is available today and has a wide variety of compatible power distribution and IT equipment. However, in very large data centers with centralized distribution systems, 48V DC will have higher cable and/or bus bar costs associated with high currents and long runs. 550V DC overcomes the distribution losses associated with centralized 48V DC. It maintains good efficiency and compatibility with existing 48V DC power distribution and IT equipment. However, the 550V DC would likely not be the most efficient choice. 380V DC appears to promise the highest efficiency but will require the introduction of new products, including UPSs, and changes to IT equipment power supplies. Future publications from The Green Grid will address each configuration in a more detailed, quantitative manner.