

AC Versus DC Power Distribution

Issues to consider when comparing options for improving data center energy efficiency

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Executive summary

Looking to save money, enhance sustainability and ease compliance with environmental regulations, data center operators around the world are eagerly investigating new energy efficiency strategies. The most effective such strategies generally involve distributing power to IT loads at higher voltages, something data centers can do using either AC or DC power. This white paper discusses the leading AC- and DC-based distribution alternatives, examines their relative advantages and disadvantages and then proposes a new AC distribution option capable of reducing energy waste as much as DC distribution does at a lower cost and with fewer safety and reliability issues.

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Options for increasing data center efficiency

Data center managers can boost power efficiency in a variety of ways. The system configuration in figure 1, which is representative of most North American data centers today, serves as a baseline scenario for examining those options and their relative impact.

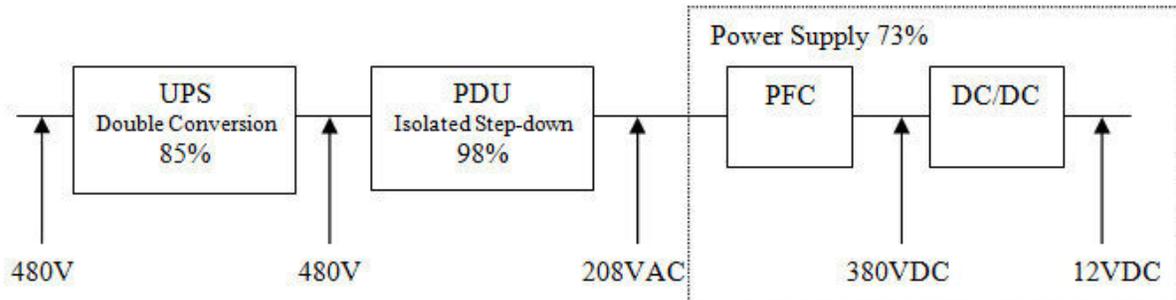


Figure 1. Baseline efficiency power chain.

The power source in figure 1 is 480V delta, which is the most common power source in North America. Backup power is provided by a traditional uninterruptible power system (UPS) operating in double-conversion mode. The UPS supports a localized power distribution unit (PDU) step-down isolation transformer that supplies 208/120V power to the loads.

This approach to powering the data center is approximately 61 percent efficient when measured from the source to 12VDC within the IT load. However, simply upgrading the UPS, PDU and other components to newer models, as illustrated in figure 2, allows us to increase efficiency to 83 percent.

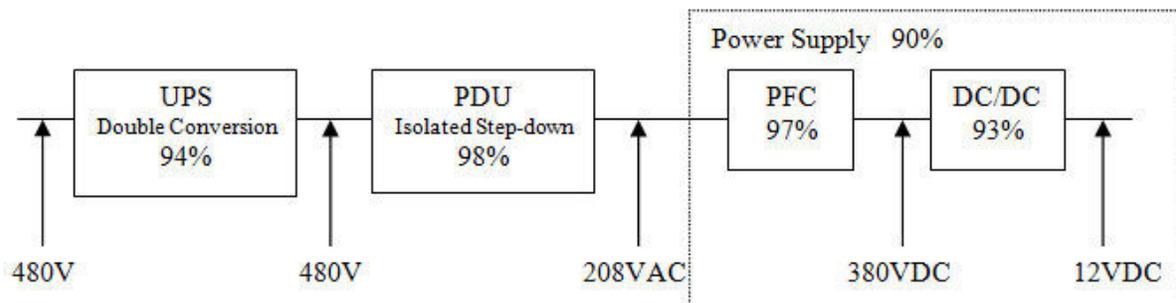


Figure 2. Power chain using newer components.

Using UPS hardware with a high-efficiency operating mode

Companies can further improve efficiency to 87.5 percent by deploying state-of-the-art UPS hardware with an automatic high-efficiency mode, as depicted in figure 3.

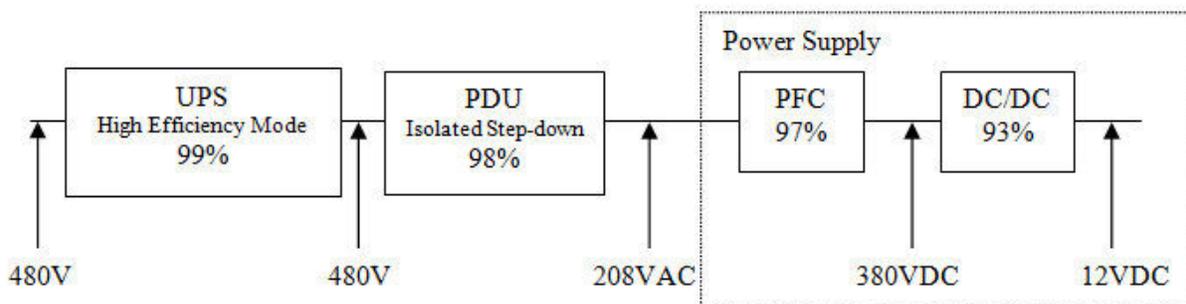


Figure 3. Power chain using UPS hardware with a high-efficiency operating mode.

Passing utility power directly to a server's power supply eliminates power conversion stages, thereby reducing energy waste. In the past, however, most power supplies were incapable of running properly on utility voltage. Today's server power supplies have power factor corrected (PFC) front ends that extend their input voltage range while maintaining a strong power factor. As a result, they're capable of operating safely on direct utility power, provided voltage stays within an acceptable input range. High-efficiency UPS hardware capitalizes on this fact by passing utility power directly to servers when voltage is within the acceptable range and switching automatically to double-conversion mode whenever voltage falls outside that range.

Transitioning almost instantaneously from one mode to another like that requires sub-cycle transfer times between the source and the inverter. High-efficiency UPSs typically feature SCR-based switches that employ special techniques to commutate the silicon-controlled rectifier (SCR) current so the load can be quickly isolated from the source and the inverter can supply the load.

State-of-the-art UPSs also use special methods when operating in high-efficiency mode to respond to load-side and source-side faults. After a load-side fault, they maintain the source connection, due to the utility power's significant fault clearing capability. Alternately, after a source-side fault, they automatically disconnect the source and transfer to inverter mode. Both load-side and source-side faults may result in near zero load voltage and high currents, but high-efficiency UPSs come with sophisticated technology that enables them to determine a fault's exact location.

High-efficiency UPSs can be equipped to enable mode transfer times of 0 - 4 ms. To support transfer times that short, such systems exploit the ride-through time inherent in server power supplies. Those supplies have sufficient bulk capacitance to maintain the load during the utility's normal pulsating waveform.

Eliminating the PDU and raising distribution voltage

Removing the PDU step-down transformer from the power chain and distributing power at a higher voltage raises efficiency even further. Figure 4, for example, shows a configuration with no PDU that replaces 208/120V distribution with 480/277V distribution.

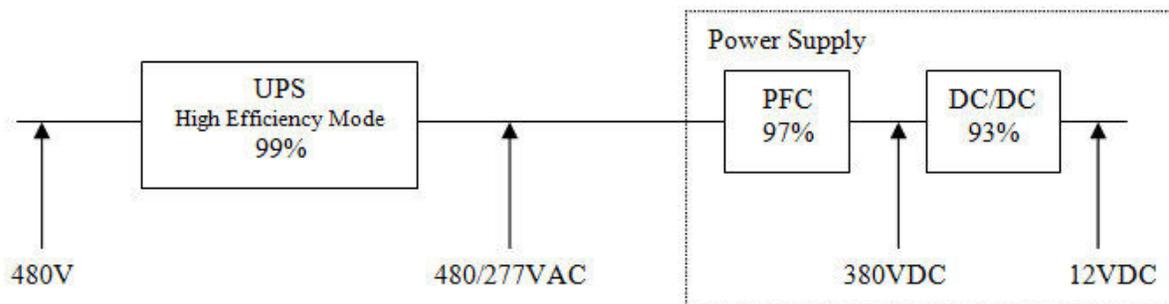


Figure 4. Power chain with no PDU that distributes 480/277V power.

Unfortunately, few power supplies support 277V input, making 480/277V distribution an impractical option for most data centers. On the other hand, 400/230V distribution, as illustrated in figure 5, is a significantly more realistic alternative that increases energy efficiency to 89 percent. In fact, most European data centers already utilize 400/230V distribution. As a result, European voltage equivalents are available for most of the IT equipment that North American data centers use today, meaning businesses can collect the benefits of increasing distribution voltage without having to deploy special power supplies. The copper conductors would need to be larger to support the same load, however, due to the reduced voltage (240V vs. 277V).

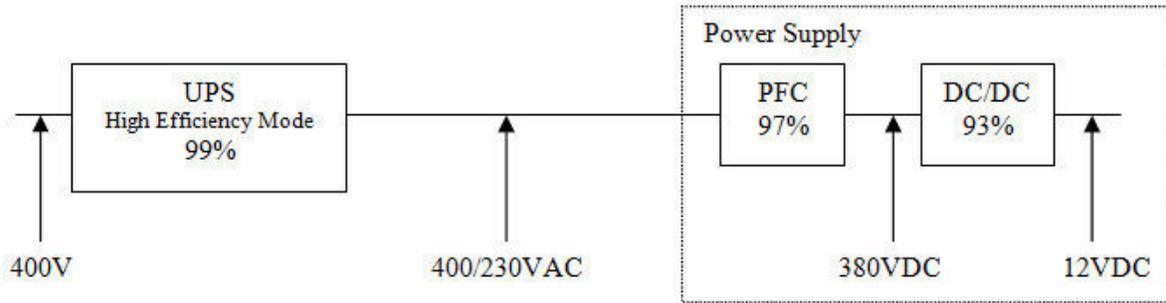


Figure 5. Power chain with no PDU that distributes 400/230V power.

Using DC power distribution

DC power systems are another means of reducing conversion stages along the power chain and distributing power at higher voltages. A typical DC system distributes power at approximately 380V DC using one of two methodologies: a wide-range voltage (+10 percent / -20 percent) methodology that accommodates direct connection of the battery backup and a narrow-range voltage (\pm percent) methodology that requires a DC/DC converter to stabilize the bus voltage during battery discharge/recharge. Both methodologies obtain DC power using an AC/DC converter. Figure 6 shows a narrow-range voltage distribution system, which is 86 percent efficient.

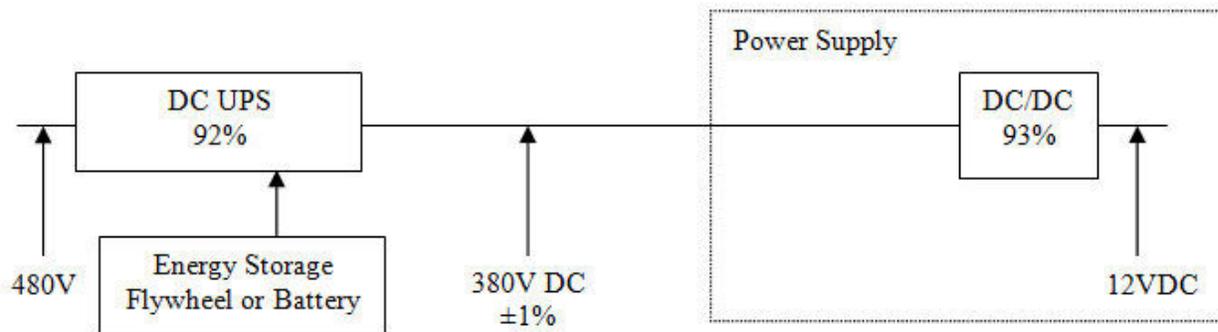


Figure 6. Power chain using narrow voltage range DC distribution.

Figure 7 shows a representative wide-range distribution system that allows the battery backup to be directly connected to the 380V DC bus. That direct connection, in turn, means that the power supplies must operate over the entire battery voltage range (+10 percent to -20 percent of 380V) while the battery is charging and discharging. Expanding the input range in this manner reduces the power supply's efficiency. Figure 7 shows a wide-range voltage distribution system, which is 84 percent efficient.

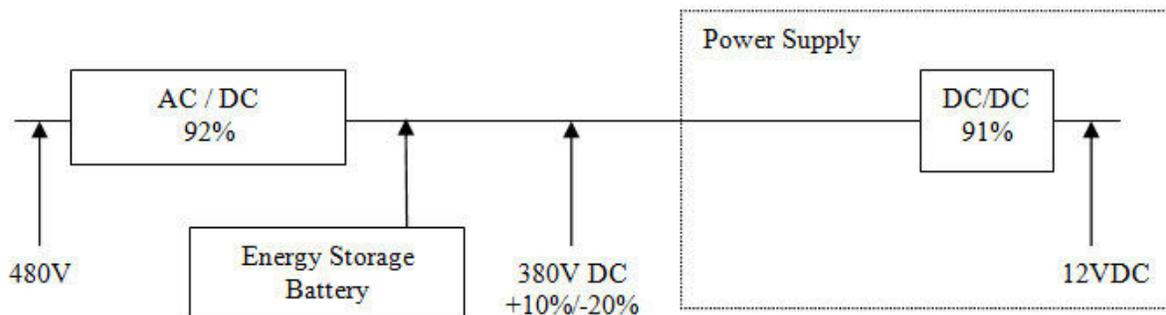


Figure 7. Power chain using wide voltage range DC distribution.

Comparing system efficiencies

Table 1 shows the extent to which each of the efficiency enhancements discussed above improves data center energy efficiency.

| System Description | System Efficiency |
|---|-------------------|
| AC, baseline efficiency scenario | 61% |
| AC, newer system components | 83% |
| AC, introduction of UPS with high-efficiency mode | 87.5% |
| AC, eliminating the PDU and distributing 480/277V | 89% |
| AC, eliminating the PDU and distributing 400/230V | 89% |
| DC, narrow voltage range distribution | 86% |
| DC, wide voltage range distribution | 84% |

Table 1. Comparison of efficiency enhancements.

As these figures make clear, data centers with AC distribution and high-efficiency mode UPS hardware enjoy the same or better efficiency than facilities that use DC distribution. AC distribution, however, has the advantage of being significantly more familiar to most data center operators.

Note that the system efficiency figures above are based on single-source distribution. Many data centers deploy redundant sources (i.e. A and B feeds) to the loads. This typically reduces efficiencies to the extent that cutting the load in half on each source alters the operating point of the converters.

Considerations before deploying DC distribution systems

Data center managers who intend to utilize DC distribution must take the following considerations into account:

- DC installations have a limitation of short circuit current values
- DC distribution requires specialized protective devices
 - Additional poles are required for breaking current for >250VDC
 - Limited discrimination between short circuit protective devices
 - Difficulty in selecting short circuit protective devices
 - Slow response of protective devices due to low short circuit current values
- Difficult to protect against electrical shock
- Corrosion of building components due to DC leakage currents
- Increased risk of fire because of serial and parallel arc faults
- Potential loss of load due to incorrect DC/DC bulk capacitor value
- Segregation between AC and DC circuits (many data centers have both)
- Limited availability of qualified and trained technicians with DC experience
- Undefined arc flash incident energy levels, which can complicate safety procedures

Although this list might stir some debate, it is a reasonable check list of considerations for anyone deploying a DC distribution system. Practical techniques are available for mitigating most of these limitations. For example, data centers can protect loads using arc fault detection and new fault-limiting PDUs. Specialized training and personal protective equipment (PPE) can be provided to personnel that maintain and install DC equipment. However, there is no universal answer to the following, more difficult problems:

- Coordination of DC/DC supply holdup time versus fault clearing time
- Selecting fault protection devices for all conditions

Coordinating DC/DC holdup time versus fault clearing time

In a DC distribution scheme, the DC/DC converter at the load must store sufficient energy in the capacitors to meet the system's ride through time requirements. This ride through time defines how long IT equipment can continue to function during an interruption in the DC source.

Interruptions of this kind can occur in response to a DC bus fault, and their duration is the length of time required to isolate the fault. The DC system design must account for the clearing time of any protective elements. If the system includes a battery backup, the fault clearing time must be determined for both system normal and battery backup modes. Available fault current must be determined to clear the protective elements in the required holdup time within the IT supply and enable adequate selective tripping. Based on the available fault current and protective element selection, the capacitor required to support the system ride through time may be much larger in the DC power supply unit (PSU) than the equivalent AC PSU.

During a fault, all PSUs will see a drop in the DC bus for as long as it takes to clear and isolate the fault. When the bus recovers, there will be a current surge to recover the capacitor storage in each PSU. The demand that this current surge places on a DC power supply with finite current sourcing capability will extend the length of the recovery event. Therefore, selecting the appropriate DC/DC converter for a DC distribution system requires a thorough understanding of that system's fault clearing time.

In AC distribution systems, the utility supplies significant fault clearing current, making it easier to select proper fault protection and provide selective tripping protection for the other loads on the common AC bus. When an AC UPS is deployed, the utility supplies this fault clearing current when the UPS switches to bypass mode. Therefore, replacing the AC system with a DC system requires both forethought and detailed knowledge of the DC system components contained within the IT load.

Using the DC source does eliminate the need for the PFC input stage that draws sine wave utility current and maintains the working DC voltage on the bulk storage capacitor. The output stage operates from the DC voltage to produce the required output. The removal of the PFC does not automatically eliminate the need for the bulk storage capacitor or the inrush limiter. The bulk capacitor provides energy storage that will support the load while the upstream protective element clears the fault. Although we have switched to DC power, the need for the bulk capacitor and a rectifier to isolate the energy storage from the fault has not diminished. Depending on the choice of protective element and system impedance, load support times may be increased, requiring larger values of the microfarad per watt bulk capacitor, as discussed above.

Selecting fault protection devices

DC protective elements need to isolate faults quickly to prevent the collapse of the common distributed DC voltage. The response time of the protective element is dependent on the impedance of the DC system. DC systems have finite current capability, as the bus is supplied by converters that tend to limit current so as to protect themselves. Unlike AC distribution systems, DC configurations have no "infinite" current source (i.e. the AC utility) to aid them in fault-clearing protective devices.

Fuses for protective elements must therefore be selected carefully. The inductance in a DC circuit limits the rate at which current rises. The rate at which current rises influences the melting time-current characteristic and the peak current let-through. In one of the proposed DC topologies discussed earlier in this white paper, the battery is connected directly across the DC voltage bus. The battery has a wider voltage operation range, requiring the DC/DC converter in the IT equipment to have a wider input voltage range.

There is a hidden problem with this arrangement, however: The protective elements are expected to operate in both normal and backup modes, but the available short circuit current can be different in each case. This can lead to longer fault clearing times in backup mode.

In addition, choosing the best protective element hinges on detailed knowledge of the battery's characteristics under fault conditions, and the large number and variety of battery types available makes acquiring that knowledge difficult. Moreover, fault current under short circuit conditions is further limited by the internal impedance, and therefore state of charge, of the battery.

Clearly, then, protective elements should not be selected casually when deploying a DC system. Thorough information about the specific DC implementation must be assembled beforehand.

Safety in the DC data center

The classic argument about the relative dangers of AC and DC power is ultimately pointless. Though it takes more current for DC power to reach lethal levels, at a data center's typical operating voltages both AC and DC power have more than enough potential energy to pose deadly threats.

One DC-specific safety issue worth focusing on, however, concerns areas in the data center where human contact with live electrical elements is possible, especially plug connections. Until relatively recently, standard connectors for plugging in high-voltage DC data center equipment did not exist. Now several high-voltage, DC-rated plugs designed to function much like AC plugs have begun reaching market. Some of these plugs are rated to disconnect DC current. However, DC power has a tendency to arc when current is interrupted, which can cause carbon deposits and other arc byproducts to build up on the plug body. Over time, these byproducts have the potential to provide a conductive path that may reduce the spacing between the DC conductors and the user.

Arc faults are a major concern for DC distribution systems. Unlike AC power, DC provides no zero current intervals to allow the arc product to cool, thus extinguishing the arc. With DC power there is a real possibility of series and parallel arcs occurring due to conductor damage or resistive connections. Once an arc starts, it can quickly lead to a fire. PDUs that have electronic current limiting and arc fault detection should be used to mitigate this risk.

One option for improving user safety in a DC environment is to install the equivalent of AC ground fault type protection. However, it would be difficult in such a scenario to detect low-level currents with simple current sensors. For example, a LEM (current) sensor with one percent accuracy cannot sense a 1mA change (i.e. at 20A we could have a 200mA error.). This would tend to increase the complexity and cost of effective DC ground fault protection.

Reliability in the DC data center

Although DC power distribution simplifies paralleling of sources, the argument that DC systems are more reliable because they have fewer conversion stages is somewhat misleading. While there are indeed fewer conversion stages in a DC system, there is more to reliability than just conversion stages.

For example, the ability to isolate a fault without compromising the remainder of the load is an important aspect of system reliability. DC systems are supplied by a rectifier that has a finite current sourcing capability. This may require fast-responding fuses or circuit breakers as protective elements to achieve the required fault clearing time. Fuses, for instance, must have sufficient fault current to be cleared quickly. If the fault current is reduced or limited, the fault clearing time is extended. If the batteries provide part of the expected fault current, they cannot be removed from the DC bus without creating a potential reliability issue, since the fault clearing current will not be as expected. Unlike AC systems, DC systems do not have a nearly infinite current source capability from the utility that can be used to provide high fault currents to clear the protective elements quickly.

Also, achieving high system reliability in a DC environment may require implementing voltage disturbance mitigation to avoid the resonant voltage (i.e. ringing) that can occur between the system's capacitance and inductance. This resonant voltage is most pronounced when a protective element opens to isolate a shorted load. Unless this resonant voltage is controlled, it will adversely affect the load's operational voltage range.

Since these effects are system dependent, careful planning, component selection and layout are required to achieve the expected system reliability gain over an AC distribution system.

Using European distribution voltages to increase AC efficiency

Of the options for increasing data center energy efficiency discussed earlier in this white paper, all but the first two, illustrated in figures 2 and 3, require disruptive, expensive and time-consuming changes. As a result, they are best employed in new data centers instead of existing ones. Adopting the higher distribution

voltages commonly used in European countries, however, potentially offers North American data center operators a means of boosting efficiency in an existing facility without significantly impacting operations or sacrificing the familiarity of AC distribution.

Still, U.S. data centers that wish to use European voltages must first address several technical issues. For one, most distribution schemes in the U.S. currently employ a localized PDU transformer to step power down from 480V delta to 208/120V wye without providing the neutral from the 480V source. To adapt this arrangement for European voltages, organizations could use a 3-wire to 4-wire conversion via the delta to wye isolation transformer. Currently, the isolation transformer is the only solution recognized and allowed by the NEC for the delta to wye conversion.

Yet while European distribution voltages are suitable for most U.S. IT loads, the load voltage they deliver is 17 percent less than what is provided by 480/277V distribution (i.e. 415/240V). Moreover, significantly more copper conductor is required to support the same kVA load. This increased copper requirement is most pronounced in implementations of the sort depicted in figure 5, due to the increased conductor size and the additional neutral wire required by the wye distribution.

A better alternative would be to distribute 480V delta to the point of use and then convert it to 480/277V or 400/230V distribution. At present, however, such an arrangement would require specialized transformers to provide the final distribution voltages. The dilemma is that most of the U.S. has 480V delta source distribution. Even when the 480V source is wye, the neutral is not usually supplied with the source conductors and instead is kept at the HV to LV transformation location. There are, however, two new solutions that could potentially overcome this quandary.

First proposed solution

Transformers that utilize the “auto-zigzag construction” shown in figure 7 can perform the delta to wye transformation without the efficiency loss of an isolation transformer. Auto-zigzag construction provides the common functions of zigzag grounding autotransformer and autotransformer. It also provides a voltage transformation and establishes a stable neutral from the 3-wire delta input regardless of phase-to-neutral loading, including 100 percent imbalance. The combined structure is very efficient, improves load balance to the mains and has the benefit of harmonic mitigation from the distribution source. It also establishes a local load “neutral” that can isolate load groups in larger deployments.

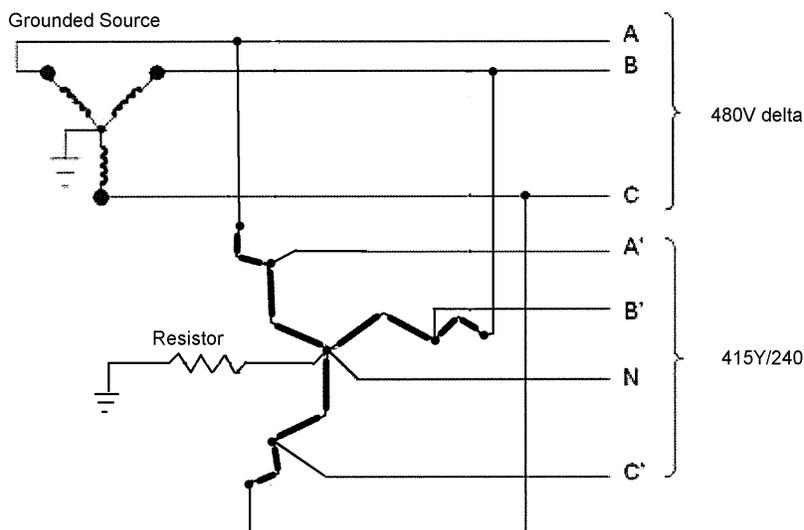


Figure 7. Auto-zigzag transformer structure.

Unfortunately, auto-zigzag construction is not allowed under the current NEC. If we could overcome the limitations of NEC Articles 450, 210.9 and 250.36, the autotransformer would provide an efficient and effective transformation from the 480V delta to 400/230V wye distribution.

The installation would need to meet the following characteristics:

- Source is 480V delta
- Ground resistors are used to connect derived neutral to ground
- Monitoring of the ground resistor voltage causes an alarm to sound if excessive voltage is detected
- Breaker protection for the auto-zigzag transformer opens three source phases simultaneously
- Loads have two-pole breakers

A 650 kVA auto-zigzag transformer of this construction has been successfully tested. This construction has a 1.5 percent impedance vs. 5.75 percent for a typical isolation transformer and the efficiency of an autotransformer.

Second proposed solution

As discussed above, European distribution voltages can support most IT loads without specialized power supplies. However, IT loads generally have a single phase input voltage requirement. Although the typical European distribution is a wye with a neutral, there is no technical reason to provide a common “neutral” voltage to support single-phase loads other than the reduction in the number of conductors required.

Modifying the standard auto-zigzag transformer structure so that it supplies power to the load as three separate 240V single-phase circuits, as depicted in figure 8, gives us similar performance in a manner that’s not specifically prohibited by the NEC. On the other hand, it’s not explicitly permitted either. That ambiguity ultimately leaves the decision as to whether data centers can use the modified auto-zigzag structure up to the various “authorities having jurisdiction” across the country, with results that are hard to predict.

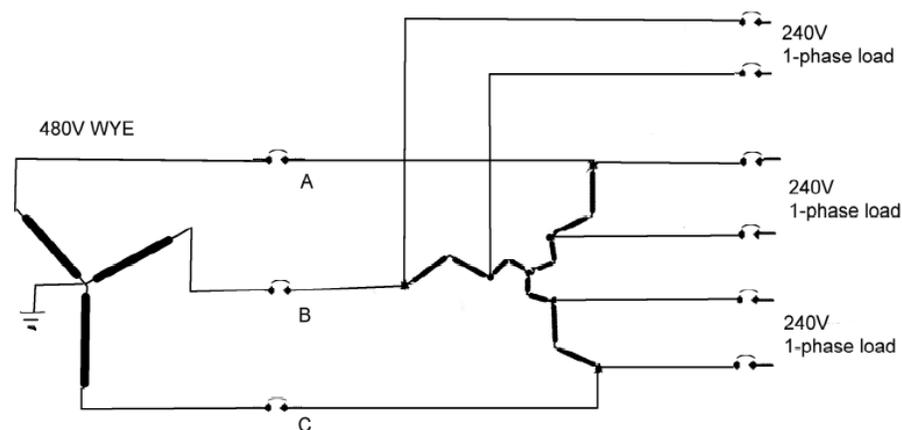


Figure 8. Modified auto-zigzag transformer structure.

Employing the modified auto-zigzag structure will therefore remain risky until the NEC has been updated. While not simple, however, updating the NEC is likely to be quicker, easier and less expensive in the long run than making the kind of wholesale data center infrastructure changes required by efficiency schemes that involve switching from AC to DC distribution.

Conclusion

Organizations seeking to increase data center efficiency have a variety of options. In North America, those with the biggest impact generally entail distributing power at increased voltages. This goal can be achieved using either AC or DC power. However, while either approach offers roughly the same efficiency gains, DC-based distributions expose data center operators to a variety of technical obstacles. Companies that wish to use DC distribution should familiarize themselves with these obstacles and verify that they have workable countermeasures for each of them. Alternatively, if the appropriate authorities can be persuaded to update the NEC, data center managers can use auto-zigzag transformers to enjoy the efficiency benefits of high-voltage distribution without DC distribution’s added costs and complexities.

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Robert W. Johnson is chief engineer for platform development and intellectual property in the global power converter platforms group at Eaton Corporation. Over the last 44 years, he has shaped the technology in the power conversion industry covering small and large-scale UPSs as an employee of Powerware, now Eaton Corporation. He has substantially contributed to making the company a recognized technology leader in the field. Major technology innovations cover a wide range of subjects and are recognized with over 40 industry patents and 11 patent applications pending to his credit. Bob was the inaugural 2004 Electrical EOY winner. He was recognized for the Minimally Switched Topology and Global On-line Platform which streamlined the quantity of platforms by leveraging reusable designs in the execution of leading technology in the power conversion industry. This standardization, unique in the industry, results in more mature designs, lower cost, simplified supply chain, reduced inventory, higher reliability and lower maintenance costs. The leading technology has increased efficiencies and performance that has resulted in higher power densities, lower costs, reduced inventory and reduced maintenance costs.