Edison's Data Center: 380Vdc brings Reliability and Efficiency to Sustainable Data Centers

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Direct-current (DC) technology has changed significantly over the last 120+ years since Edison and Westinghouse publically battled over DC vs. AC in the War of Currents. In the nineteenth century, AC became the dominant power distribution design because transformers cheaply solved the problem of getting power more than a kilometer from a centralized power station. Even with over a century of new technology, we never looked back.

Yet, today, the world faces unprecedented issues with global climate change and the need for sustainability. And the technology that eluded Edison in the 19th century makes DC the distribution of choice for the 21st century. If Edison were here today, his data center would be DC.

I. Overview

For years, most data center operators focused primarily on providing enough compute capacity to meet demand and provide adequate cooling. But as businesses, organizations and governments have become increasingly dependent on data centers for practically everything they do (from day-to-day operations to electronic transactions and communications), the cost of powering these data centers has gained greater attention. Equally worrisome, many facilities have outgrown the power capacity for which they were designed.

The total power consumption of today's data centers is becoming noticeable. According to the U.S. Environmental Protection Agency (EPA), data centers and servers in the United States accounted for approximately 1.5-percent of the U.S. total electricity consumption in 2006. To put this in perspective, the EPA notes that this is more than the electricity consumed by the nation's color televisions and is "similar to the amount of electricity consumed by approximately 5.8 million average U.S. households (or around five percent of the total U.S. housing stock)." While data centers enable energy savings in the rest of the economy by allowing us to "work smarter," e.g. through telecommuting or banking on-line, their growing energy utilization is something the EPA thinks that we can address by adopting energy efficient technologies. One prominent example is 380 Vdc electrical power distribution.

Since the 1960's semiconductors (natively DC) have come to dominate our electrical devices such that soon the majority of the load-base will be natively DC. Most of the carbon-free energy sources and energy storage are natively DC. Furthermore they are being deployed in a distributed manner. Thus, the assumptions that gave us AC power distribution are necessarily being re-examined and a fundamental shift to DC is well underway.

In this article, we look at Low Voltage Direct-Current (LVDC) at 380 Vdc and the new industry specification and single worldwide standard in datacenters (and envisioned for the entirety of future commercial buildings). Starting with the motivations – and in the context of the changing environment – we look at the development of 380 Vdc, its current implementation as a ±190 Vdc distribution with midpoint ground (figures 1 and 2) and the resulting benefits. That leads to articulating the case for LVDC, as well as debunking several common myths that no longer apply. Finally, the article concludes with some notable examples of 380Vdc data centers from around the world.

II. The Wakeup Call

As a result of the electricity supply issues in California at the beginning of the 2000's, the California Energy Commission triggered a 10-year research initiative around high-tech buildings (data centers). The idea was to research, develop and demonstrate innovative energy efficient technologies and use demonstration projects to accelerate the deployment of results.

In 2004 Lawrence Berkley National Laboratory (LBNL) started investigating the efficiency of power distribution in data centers. By 2005 they had studied the efficiency of power supplies in IT equipment and UPS systems. They noticed the poor efficiencies of these components and introduced the concept of eliminating some of the power conversions. This led to a DC data center demonstration sponsored by the California Energy Commission's Public Interest Energy Research Program. LBNL brought in the Electric Power Research Institute (EPRI) as a sub-contractor and started the investigation in earnest. By June of 2006 they had a public demonstration put together with the help of 16 other organizations and 14 other stakeholders.

The results were stunning: 28% efficiency improvement over the then current average AC distribution efficiency in the United States. Figure 3 shows the comparison of the two approaches with AC on the left and DC on the right.

In an AC distribution, medium voltage (MV) is transformed to 480 Vac, 3-phase at the entrance to the data center facility. For reliability reasons, the power is typically then fed to an uninterruptable power supply (UPS). The 480 Vac, 3-phase power is rectified to 540 Vdc to keep a minimum amount of energy in readiness to run the data center in the event of grid supply failure. The 540 Vdc is then converted back to 480 Vac (which also cleans up the quality of the power, as well) and is distributed to the floor of the data center. Power Distribution Units (PDUs) are scattered around the data center to convert the 480 Vac to 208 Vac, which is what runs each server. In high-reliability data centers the power is run twice to each server, which has redundant power supply units (PSU) in them, a configuration called dual corded.

Finally, the PSU produces a 12 Vdc output and derives other voltages from that to run the server electronics at voltages that generally range from 1-3.3 Vdc. In doing so the power supply internally converts the AC to unfiltered DC with a bridge. It takes that power and delivers it to a Power Factor Correction (PFC) unit to minimize the reactive power load on the incoming supply, which also boosts it to 380 Vdc internally. Modern switching power supplies implement a DC-to-DC converter to take the 380 Vdc down to 12 Vdc very efficiently.

All of the distribution voltage conversions across the data center and in the PSU, are reflective of the practices developed over the whole of the 20th century, and had never really been questioned. But herein lies the problem. Every conversion wastes energy and produces heat. And while any single conversion may be in the mid 90 percent range, they don't add together, they multiply. And when you add in the energy to remove the heat, too, it is only about 50% of the energy at the wall of the data center that actually gets used by the processors in the servers (see Figure 4). In many data centers at the time of the study the power for cooling could approximate the direct losses along the distribution path.

The first two secrets of efficiency are 1) eliminate the conversions (less waste heat generated) and 2) use as high a voltage as you can (to make the fixed losses as low an overhead as possible). Thus in the 380 Vdc distribution (right side of Figure 3) the MV was converted to 480 Vac and then immediately rectified to 380Vdc and kept there all the way through the data center distribution even into the PSU.

With the goal of being able to quickly move to implementation, the study also focused on keeping the same form factor, and using standard high-volume components. It also made sure not to compromise the existing server performance, reliability, and safety. In addition, high value was given to compatibility with alternative energy solutions such as photovoltaic (PV), fuel cells, etc. And the demonstration included DC lighting, as well. Figure 5 is a picture of the full demonstration. Thus, by eliminating the conversions the LBNL demo showed a stunning efficiency improvement with identical performance and, analytically, no reliability or safety issues.

III. The Advantages of 380 Vdc

Subsequent research and development was able to fully articulate the benefits and advantages of 380 Vdc for the data center. They include:

- 28% more efficient than 208 Vac systems at that time
- 7% more efficient than 415 Vac
- 15% less up-front capital cost in production volumes
- 33% less floor space
- 36% lower lifetime cost

- 1000% more reliable
- 20-100x less copper than -48 Vdc
- No Harmonics, and Safe

Let's look at each one in turn, starting with the most important.

Higher Reliability. This is the foremost advantage of 380 Vdc in the data center. By eliminating the extra conversions, the PDUs and transformers, front end of the PSU, and most especially the inverter that was on the output of the UPS in the AC design, the reliability of the power delivery chain is improved by 1,000%. This should not have been a surprise; this is exactly the reason that Telcos have been using -48Vdc systems for decades. And in fact in 2010 when Intel surveyed its manufacturing organization it found that of the handful of critical failures that year in the data centers that support manufacturing, the vast majority of them had to do with failures of this particular part of the data center power distribution.

In 2008 Intel, HP / EYP and Emerson Network Power did a study of applying 380 Vdc distribution to a proposed build out of the Intel JFS1 data center Module C in Hillsboro, Oregon. JFS1 Module C was a 5 MW data center design that was cancelled with the economic downturn however the results were published in 2010. In the analysis, the reliability differences were an order of magnitude better with 380 Vdc, as shown in Table 1.

Higher Efficiency. 380Vdc is 28% more efficient than the current practices for 208 Vac. The Green Grid did a peer review of the LBNL findings and agreed that the efficiency findings were real; they went on to emphasize that there are techniques that could be adopted by AC distribution from 380 Vdc, and that the real efficiency gain of note was the 5-7% that was unique to 380 Vdc. In the Intel, HP/EYP, Emerson Network Power study the efficiency gain was calculated at 7% for dual corded and 8% otherwise versus 415 Vac. Real implementations at Duke Energy and Green.ch found 15% and 10%, respectively. Thus, if you are replacing an existing legacy data center power distribution system, your gain could be as high as 28%. Or at least 7-8% for a greenfield data center, depending on if it is dual corded or not.

Lower Cost. Given that you are vastly simplifying the power distribution system and eliminating components, the cost in volume production is expected to be 15% less. Of course, until product volumes are great enough, one can expect a slight premium until enough volume and competition drives the price down. ABB and Green.ch reported that the cost for the 380 Vdc system built in Zurich this year was 10% less than for the AC system. (The Green.ch data center has both.)

In fact, lower capital and operating cost is the reason that 380 Vdc is the ideal voltage today. The third secret of making a costeffective, efficient voltage distribution standard is to stay below 420 volts to use parts that share the volume economics with PC desktop PSUs. That is why the industry selected 380 Vdc (and a specification that requires operation up to 400 Vdc and must survive exposure of up to 410 Vdc).

Finally, when you factor in the cost of real estate and the footprint savings, GE and Validus DC Systems estimate a 36% lower lifetime cost.

Less Space & Fewer Materials. The Intel, HP / EYP, Emerson Network Power study found that the footprint of the power distribution system is 33% smaller than for AC. The power supply is also reduced 30% by volume because of the elimination of components. While that is unlikely to drive to smaller PSUs (because servers will desire to use either AC or DC PSUs during the changeover), it definitely makes the 380 Vdc PSUs more sustainable. They use less of the earth's resources and have less to recycle at their end of life.

With respect to the wiring plant, 380 Vdc uses less copper than AC, even 415 Vac. Figure 6 shows the relative cross section of copper needed to carry the same amount of power. Because of skin effect and the reactive current overhead, AC conductors need to be sized bigger than DC for the same voltage and power capacity. By comparison, we can also see why Telcos and Japan are looking to wholesale replace -48Vdc with 380 Vdc. In fact, some organizations are looking at paying for the conversion simply from the salvage value of the -48Vdc copper bus bars and conductors that they replace.

No Harmonics. When you build AC data centers you are plagued by harmonics whenever you have to run UPSes in parallel. With 380 Vdc that is not an issue. In fact most 380 Vdc rectifiers on the market today are built for modular expansion in relatively small 5-15 kW increments that just stack in a rack and can be configured for redundant and/or parallel operation.

Safety. 380 Vdc is a hazardous energy, no more or less than AC at these voltages. Saying it is more or less hazardous than AC should not be the issue; it's enough that both AC and DC at these voltages are hazardous. National and international standards exist for the proper safety procedures for both AC and DC and they need to be followed.

At the same time, the data does exist and it tends to show DC is actually safer than AC at the same voltages. Table 2 shows the review of the IEC safety data that IEC 23E WG 2 analyzed, and 380Vdc distributed at ±190 Vdc is actually as safe as 208 Vac up to 250Vac. This actually becomes problematic for some of the proposed higher efficiency AC alternatives. Finally, Figure 7 shows the voltage profile across the entire distribution. Not only is 380 Vdc simpler in having fewer conversions and parts, it also has significantly lower peak voltages – the mechanism that initiates skin resistance breakdown – than current AC distribution across the entire data center.

IV. Debunking Common Myths

There are several myths that persist about DC, in general and 380 Vdc, specifically. A couple of these myths warrant debunking here, especially with respect to efficiency, danger, zero-crossing and bulky conductors or short cable run limitations.

DC is only 1 or 2 % more efficient. False. The foregoing data clearly supports that 380 Vdc is 7-8% more efficient than Low Voltage AC will ever be. The Green Grid Peer Review of the LBNL study agreed that the findings were correct and that after the AC distribution incorporated the Vdc best practices it could, including minimize conversions, 380 Vdc was still 5-7% more efficient. If you limit yourself to only the electrical domain, or a subset of the distribution, and some unrealistic assumptions one can probably construct a system boundary where the analysis might show a small number. Frequently these claims gloss over the energy needed to remove the waste heat or other DC power potential applications (e.g. variable speed drives), which could be a significant multiplier. Moreover, every implementation to date has *measured* a real efficiency gain of at least 10 to 15%.

DC requires big conductors and can only go a couple of meters for a reasonable cost. While that may be true of DC at 12 or 24 or 48 volts, it is certainly not true at 380 Vdc. This is actually quite natural since we have grown up in homes where DC was regularly associated with extremely low voltage on the order of 1-50 volts, and AC was associated with higher voltages on the order of 100-250 volts. The frequency (AC vs. DC) and the voltage levels are orthogonal to each other, and any extremely low voltage – AC or DC – will require bigger conductors and shorter runs. And the converse is true that higher voltage – AC or DC – will be more efficient. This is one of several reasons the EMerge Alliance is looking at using 380 Vdc as the distribution backbone for all of commercial buildings and even campuses, and not just data centers.

Running off the battery bus eats up all your efficiency. False. While it is true that the 380 Vdc PSU is 1-2% less efficient when it has to tolerate the wide 260-400 Vdc input, it was judged more than worth it to get a 1,000% reliability gain. In the final version of the spec and standard, batteries are directly on the 380 Vdc bus and the PSU is designed to accept a wide range of input voltage. The PSU will track the battery all the way down to 260 Vdc as it discharges. This is an acceptable compromise that appropriately balances efficiency and reliability.

Arc Flash is an unacceptable hazard with 380 Vdc. False. The connectors have been specifically designed with features to fully enclose the arc for at least 5-10A currents. Moreover the standard connector is already rated for 20A; this is the 380 Vdc analog of the IEC C-13 connector for AC, or even the C-19. Connectors with magnetic arc breakers and switched interlocks exist in the market today for greater currents. And the IEC-309 connector is already fully rated for up to 450 Vdc.

AC is safer because the voltage crosses zero 50-60 times a second. If the current is not leading or lagging, it may be easier to turn off. But if that were true for servers, they wouldn't have Power Factor Correction circuits. Yet all one has to do is pop toast in an AC toaster and pull the plug to put the lie to this.

This is actually a specious argument, because the only ones who have to worry about this are the ones that make the components. An electrical system is comprised of listed components, and once the component makers have figured out how to design and certify their components, they have taken all of that responsibility upon themselves. It may cost more at a component level to design to this requirement, but once certified we only have to use it. And quite frankly, the few dollars extra at a component level pale in comparison to the millions saved at the MW level from a simpler, 10-15% less expensive power distribution system.

An AC server PSU is more efficient than a DC PSU. This can never be true for a given design. Simply clip the bridge and PFC circuits from said AC supply and it is now a 1-2% more efficient 380 Vdc supply.

V. What to Expect Next

A world-wide industry consensus is building around 380Vdc and it is being led by the 95+ member EMerge Alliance. The Alliance's vision of LVDC in the four areas of Commercial Buildings – Occupied Space, Datacenter, Building Services and Outdoors – has led to initial industry specifications for 24Vdc and 380Vdc (distributed as ±190Vdc). There are further plans to harmonize the vision and specifications into a common world-wide set of standards across all geographies with standards bodies and industry specifications such as IEC, UL, NEMA, NFPA, NEC and ETSI, as well as, the new USB 3.0 power specification. The scope of the vision encompasses everything in a campus or building microgrid from the medium voltage (MV) utility feed, alternative energy sources, energy storage and all the way down to the lights, motors, EV charging stations and furnishings. Figure 8 shows an example of the data center section of the campus including integrating AC mains and renewables with the data center distribution. Moreover, using 380 Vdc pulls in the cross-over to zero net energy buildings sooner because of the better efficiency and fewer conversions, especially with energy storage.

Around the world data centers are adopting 380 Vdc and validating the claims that have come before. The University of California San Diego 2.8MW bio-fuel fuel-cell powered data center came on line in August, 2010 (see figure 9). Duke Energy brought their data center "fly-off" online in 2011 and EPRI measured and validated a 15% efficiency gain. The Green.ch data center in Zurich, Switzerland is one of the first 380Vdc data centers in Europe. Its first phase build out is 1,100 m^2 and it consumes 1MW. It derives its input directly from MV at 16 kVac. Green.ch and ABB report that compared to the AC side, the 380 Vdc data center is

- 10% more energy efficient,
- 15% less capital cost,
- 25% smaller footprint
- 20% lower installation costs

Japan's Ministry of Economy, Trade and Industry (METI) has been pursuing a program called Green IT since 2009. Part of that program has been a drive to convert data centers to DC. 380 Vdc rectifiers have been on the Market since Q1 of 2011. When the tsunami hit Sendai in Japan last year, the NTT Facilities DC microgrid and data center supplied power to the hospital across the street for the first 2 days (see "A Microgrid That Wouldn't Quit," *IEEE Spectrum* October, 2011).

China is also committed to DC with a plan to initially convert to 240-280 Vdc, then 380 Vdc.

By the time this is published both the new version of ETSI EN 300 132-3-1 for up to 400 Vdc standard and the EMerge Alliance Data and Telecom Center industry specification – with which it is harmonized – should already be published. Figure 10 shows the Voltage Tolerance curve; it is the analog to the CBEMA Voltage Tolerance curve for the AC world.

VI. Conclusion

We are on the cusp of a great technology transition in power distribution from AC to DC at the edge of the grid. Data centers are merely one of the first industries to embrace the coming tide. The transition on the customer side of the meter is on the order of what happened over the last 40 years with personal computers, the internet and cell phones. The predominant use of power electronics in almost everything we buy new today makes them natively DC devices. As a society we could be more efficient and sustainable if we were to skip the last AC-to-DC conversion. At some point soon, when the majority of the load base is natively DC, we reach a tipping point where AC and hot power converter "bricks" on everything are no longer sustainable. Add to this distributed generation, distributed energy storage, renewable, carbon-free power sources (that prefer DC) and one can conclude that the transition is not only necessary, but inevitable.

For commercial buildings that change is going to happen in data centers first. The reasons are compelling. To wit, 380 Vdc power distribution for the data center is:

- more efficient than AC
- 15% less up-front capital cost in volume
- 33% less floor space
- 36% lower lifetime cost
- 1000% more reliable
- 20-100x less copper than -48 Vdc
- No Harmonics, and Safe

The use of 380Vdc in the data center and in commercial buildings, in general, is inherent in that transition. One hundred years from now, when people perhaps even chuckle that anyone ever used AC, Edison's data center is likely to mark an important turning point for the all DC Smart Grid.

FURTHER READING

[1] DC Power for Data Centers of the Future http://hightech.lbl.gov/dc-powering/
[2] T. Aldridge, et al, "Evaluating 400V Direct-Current for Data Centers" http://www.techonline.com/learning/techpaper/222200674
[3] DC – An idea whose time has come and gone? http://blogs.intel.com/research/2010/05/24/dc_-_an_idea_whose_time_has_co/
[4] EMerge Alliance http://emergealliance.org
[5] Environmental view of 380VDC from Yale School of Forestry & Environmental Studies: http://environment.research.yale.edu/documents/downloads/0-9/05-DC-Microgrids.pdf
[6] Jill Jonnes, *Empires of Light: Edison, Tesla, Westinghouse and the Race to Electrify the World*, Random House, 2004.

BIOGRAPHIES

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Figure 1. Midpoint resisitive grounding for the 380Vdc data center distribution at ±190Vdc (Courtesy of EPRI).

Figure 2. Earthing practice for the 380Vdc data center distribution at ±190Vdc (Courtesy of Emerson Network Power).

Figure 3: Typical North American AC distribution (left) vs. worldwide industry standard 380Vdc DC distribution (right).

Figure 4: For every 100W used by the compute load, 200-300 more Watts are typically used by the infrastructure in a data center to operate and cool the systems.

Figure 5. The LBNL 380Vdc Demonstration in 2006. (Courtesy LBNL)

JFS Mod C Power Distribution	Availability	Reliability Improvement
AC Tier IV	0.999996	--
380 Vdc w/ regulated DC bus	0.999998	200%
380 Vdc w/ direct connect to battery bus	0.9999996	1,000%

Table 1. Calculated Reliability comparison shows 380 Vdc is 1,000% more reliable for power distribution.

Figure 6: At the same power conducted, relative conductor diameter for 380 Vdc uses less copper than even high-efficiency 415 Vac. Conductors for 380 Vdc are much smaller than -48 Vdc with much less weight and less copper cost. (Courtesy UECorp)

Voltage to earth	Breaking times (s) AC	Breaking times (s) DC		
	Direct contact (IEC 60479) IΔn ac max= 30 mA	Direct contact (IEC 60479) IΔn dc max= 100 mA	Fault protection (IEC 60364-4-41)	
			TN	TT
400V	560 Ω 714 mA Not possible	560 Ω 714 mA Not possible	0,4	0,2
300V	595 Ω 500 mA Limit. Not recommended	595 Ω 500 mA Limit. Not recommended	0,4	0,2
250V	620Ω 400mA 150ms safety margin for ac is aprox. 1/4 (40 ms)	620Ω 400mA 80ms Does not allow same safety margin as for ac	0,4	0,2
200V (3 wires with mid-point ground)		640 Ω 300mA 150ms Allows comparable safety margin as for ac (1/4)	5	0,4

Table 2. Analysis of IEC protection against electric shock safety requirements shows that 380Vdc distributed as ±190 Vdc can be at least as safe as 208Vac to 250Vac. Note that 415Vac high-efficiency alternative is problematic. (Source: IEC 23E WG 2)

Figure 7: Typical North American AC distribution goes through 5 conversions on the way through the data center (red solid line). The 380Vdc distribution has two (green dotted line).

Figure 8. A generic pictogram of a 380Vdc Power Distribution System for Data and Telecom Center Applications. A data center is simply one class of usage on a whole campus / building 380Vdc microgrid backbone. (Courtesy EMerge Alliance)

Figure 9. The University of California San Diego 2.8 MW Fuel Cell powered 380Vdc Data Center since, August, 2010. (Courtesy UCSD)

Figure 10. EMerge Alliance DC-PDS DTC Voltage Tolerance Curve is the 380Vdc industry standard for the voltage tolerance envelope. It is the DC analog to the AC Computer Business Equipment Manufacturers Association (CBEMA) curve (based in turn on IEEE 446). (Courtesy EMerge Alliance)