ELECTRIC POWER
RESEARCH INSTITUTE

DC Power Production, Delivery and Utilization

An EPRI White Paper

June 2006

This paper was prepared by Karen George of EPRI Solutions, Inc., based on technical material from:

Arshad Mansoor, Vice President, EPRI Solutions
Clark Gellings, Vice President—Innovation, EPRI
Dan Rastler, Tech Leader, Distributed Resources, EPRI
Don Von Dollen, Program Director, IntelliGrid, EPRI

Acknowledgements

We would like to thank reviewers and contributors:

Phil Barker, Principal Engineer, Nova Energy Specialists
David Geary, Vice President, of Engineering, Baldwin Technologies, Inc.
Haresh Kamath, EPRI Solutions
Tom Key, Principal Technical Manager, EPRI
Annabelle Pratt, Power Architect, Intel Corporation
Mark Robinson, Vice President, Nextek Power

Edison Redux: The New AC/DC Debate

Thomas Edison's nineteenth-century electric distribution system relied on direct current (DC) power generation, delivery, and use. This pioneering system, however, turned out to be impractical and uneconomical, largely because in the 19th century, DC power generation was limited to a relatively low voltage potential and DC power could not be transmitted beyond a mile. Edison's power plants had to be local affairs, sited near the load, or the load had to be brought close to the generator.

Alternating current (AC) distribution was far superior for the needs of a robust electrical infrastructure. Unlike DC power, the voltage of AC could be stepped up with relatively simple transformer devices for distance transmission and subsequently stepped down for delivery to appliances and equipment in the home or factory. And Nikola Tesla's invention of a relatively simple AC induction motor meant end users needed AC, which could be generated at large central plants for high-voltage bulk delivery over long distances. (See the section *AC versus DC: An Historical Perspective* for more on the attributes of AC and DC power, and why AC originally prevailed.)

Despite a vigorous campaign against the adoption of alternating current, Edison could not overcome the shortcomings of his DC system. AC won out, and today utilities generate, transmit, and deliver electricity in the form of alternating current.

Although high-voltage direct current (HVDC) is now a viable means of long-distance power transmission and is used in nearly a 100 applications worldwide (see **sidebar**, *High-voltage direct current transmission, p. 6*), no one is advocating a wholesale change of the infrastructure from AC to DC, as this would be wildly impractical.

But a new debate is arising over AC versus DC: should DC power delivery systems displace or augment the AC distribution system in buildings or other small, distributed applications? Edison's original vision for a system that has DC generation, power delivery, and end-use loads may come to fruition—at least for some types of installations. Facilities such as data centers, campus-like groups of buildings, or building sub-systems may find a compelling value proposition in using DC power.

Several converging factors have spurred the recent interest in DC power delivery. One of the most important is that an increasing number of microprocessor-based electronic devices use DC power internally, converted inside the device from standard AC supply. Another factor is that new distributed resources such as solar photovoltaic (PV) arrays and fuel cells produce DC power; and batteries and other technologies store it. So why not a DC power distribution system as well? Why not eliminate the equipment that converts DC power to AC for distribution, then back again to DC at the appliance?

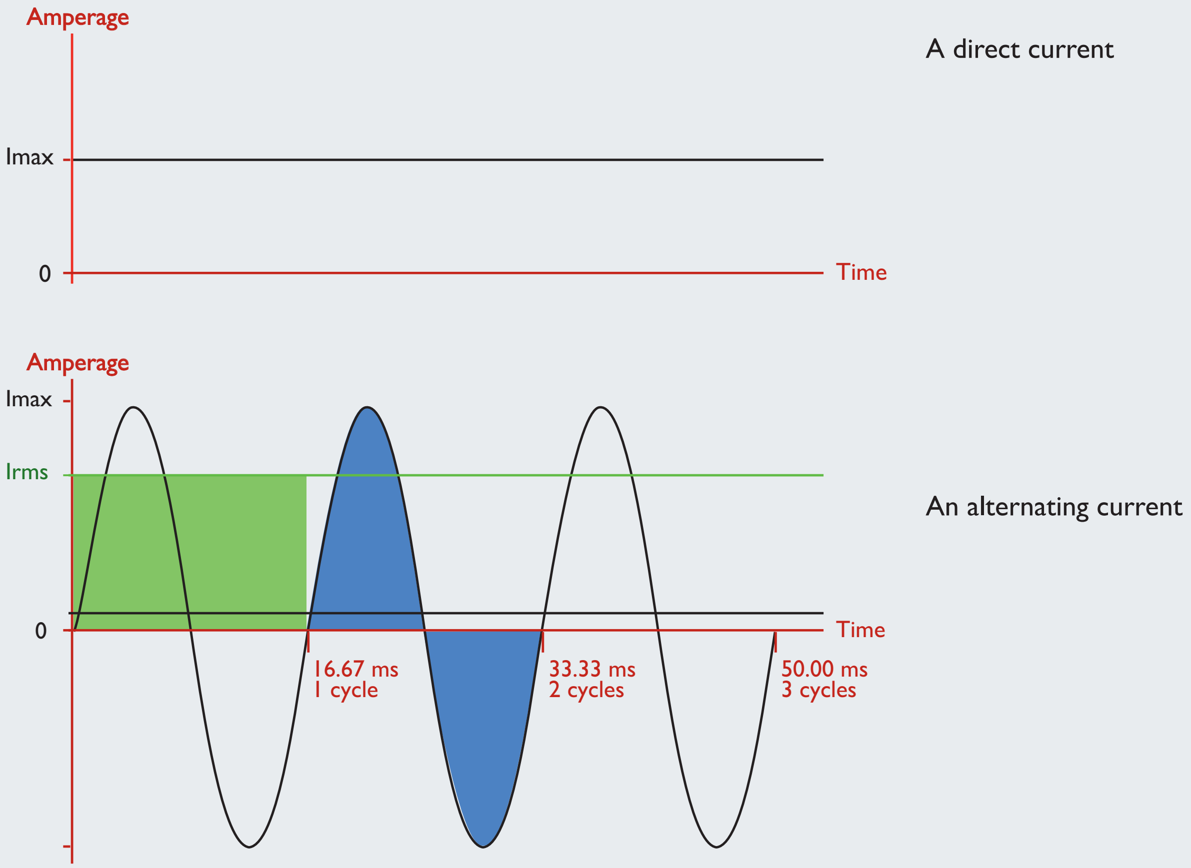
Contents

Understanding direct current and alternating current

Direct current (DC) is a continuous flow of electricity in one direction through a wire or conductor. Direct current is created by generators such as fuel cells or photovoltaic cells, and by static electricity, lightning, and batteries. It flows from a high to a low potential; for example, in a battery, from a positive to a negative pole. Any device that relies on batteries—a flashlight, a portable CD player, a laptop computer—operates on direct current. When represented graphically, DC voltage appears as a straight line, usually flat.

Alternating current (AC) is electricity that changes direction at regular intervals. It builds to a maximum voltage in one direction, decreases to zero, builds up to a maximum in the opposite direction, and then returns to zero once more. This complete sequence, or cycle, repeats, and the rate at which it repeats is called the frequency of the current. In the U.S. the AC power provided to a home outlet has a frequency of 60 cycles per second. This is expressed as 60 hertz (Hz), the hertz being a unit equal to one cycle per second.

Figure 1. Direct current versus alternating current



Note: Irms = root mean squared, a DC equivalent for same power output

Advocates point to greater efficiency and reliability from a DC power delivery system. Eliminating the need for multiple conversions could potentially prevent energy losses of up to 35%. Less waste heat and a less complicated conversion system could also potentially translate into lower maintenance requirements, longer-lived system components, and lower operating costs.

In a larger context, deployment of DC power delivery systems as part of AC/DC "hybrid" buildings—or as a DC power microgrid "island" that can operate independently of the bulk power grid—could enhance the reliability and security of the electric power system.

Benefits and drivers of DC power delivery systems

Several potential benefits are driving newfound interest in DC power delivery systems:

- **Increasingly, equipment operates on DC, requiring conversion from AC sources.** All microprocessors require direct current and many devices operate internally on DC power since it can be precisely regulated for sensitive components. Building electrical systems are fed with AC that is converted to DC at every fluorescent ballast, computer system power supply, and other electronic device. As one specialty electronics manufacturer put it, "DC is the blood of electronics."[1]

  AC-DC conversions within these devices waste power. The power supplies that convert high-voltage AC power into the low-voltage DC power needed by the electronic equipment used in commercial buildings and data centers typically operate at roughly 65% to 75% efficiency, meaning that 25 to 35% of all the energy consumed is wasted. About half the losses are from AC to DC conversions, the rest from stepping down DC voltage in DC to DC conversions. Simply getting rid of the losses from AC to DC conversion could reduce energy losses by about 10 to 20%. Likewise, an increasing number of portable gadgets such as cell phones and personal digital assistants (PDAs) require an AC-DC adapter, which also results in power losses during conversion. Considered in aggregate, the millions of AC to DC conversions necessitated for the operation of electronics extract a huge energy loss penalty.

- **Distributed generation systems produce DC power.** Many distributed generation sources such as photovoltaic cells and fuel cells—and advanced energy storage systems (batteries, flywheels, and ultra capacitors) produce energy in the form of DC power. Other devices can also be suited to DC output, such as microturbines and wind turbines. Even hybrid vehicles such as the Toyota Prius could serve as DC generators in emergencies with the right equipment to connect them to the electrical system.

  The energy losses entailed in converting DC to AC power for distribution could be eliminated with DC power delivery, enhancing efficiency and reliability and system cost-effectiveness. For instance, EPRI Solutions estimated that the total lifecycle cost of PV energy for certain DC applications could be reduced by more than 25% compared to using a conventional DC to AC approach—assuming that the specific end-use applications are carefully selected.[2] The costs of new distributed generation such as PV arrays are still high, so optimization of designs with DC power delivery may help spur adoption and efficient operation.

- **Storage devices such as batteries, flywheels and capacitors store and deliver DC power.** This again helps avoid unnecessary conversions between AC and DC.

- **DC power could help power hybrid automobiles, transit buses, and commercial fleets**, Plug-in hybrid vehicles can go greater distances on electricity than today's hybrids since they have larger batteries. These batteries store DC power, so charging them with electricity from solar photovoltaic arrays and other distributed sources could reduce reliance on gasoline, enhancing security and emergency preparedness.

- **DC power delivery could potentially enhance energy efficiency in data centers, a pressing need.** One of the most promising potential applications of DC power delivery is in data centers, which have densely packed racks of servers that use DC power. In such centers, AC is converted to DC at the uninterruptible power supply, to facilitate storage, then is converted again to push out to the servers, and is converted one more time to DC at each individual server. These conversions waste power and generate considerable heat, which must be removed by air conditioning systems, resulting in high electricity costs.

In a 10–15 megawatt (MW) data center, as much as 2–3 MW may be lost because of power conversions. As these centers install ever more dense configurations of server racks, DC power delivery systems may be a means to reduce skyrocketing power needs.

- **Improved inverters and power electronics allow DC power to be converted easily and efficiently to AC power and to different voltage levels.** Component improvements enable greater efficiency than in the past, and improve the economics of hybrid AC/DC systems. Although improved electronics also enhance AC-only systems, such enabling technology makes the DC power delivery option feasible as well.

- **The evolution of central power architecture in computers and other equipment simplifies DC power delivery systems.** At present, delivering DC to a computer requires input at multiple voltages to satisfy the power needs of various internal components (RAM, processor, etc.) Development of a central power architecture, now underway, will enable input of one standardized DC voltage at the port, streamlining delivery system design.

- **DC power delivery may enhance micro-grid system integration, operation, and performance.** A number of attributes make DC power delivery appealing for use in micro-grids. With DC distribution, solid-state switching can quickly interrupt faults, making for better reliability and power quality. If tied into the AC transmission system, a DC power micro-grid makes it easy to avoid backfeeding surplus generation and fault contributions into the bulk utility system (by the use of a rectifier that only allows one-way power flow). In addition, in a low-voltage DC system, such as would be suitable for a home or group of homes, a line of a given voltage rating can transmit much more DC power than AC power.

Of course, while DC circuits are widely used in energy-consuming devices and appliances, DC power delivery systems are not commonplace, and therefore face the obstacles any new system design or technology must overcome. For any of the benefits outlined above to be realized, testing, development, and demonstration are needed to determine the true potential and market readiness of DC power delivery, as outlined in the section “Potential Future Work and Research” on p. 26.

High-voltage direct current (HVDC) transmission

Although in Edison’s time, direct current was impractical for transmission beyond the distance of a mile, today high-voltage direct current (HVDC) can transmit bulk power over very long distances and also enables interconnection of incompatible power grids.

Valves that can convert high voltage AC to DC and back again were needed for HVDC to work, so such conversion was enabled with the development of static converters and mercury arc valves capable of handling high voltages. This technology was first deployed in 1954, for a transmission system between the island of Gotland and the Swedish mainland. The system was rated at 20 MW and 100 kV and transmitted power over 57 miles. Development in the 1960s of high-voltage thyristors made with semiconductors helped boost transmission capacity, increasing the cost-effectiveness of HVDC. Technology advances continue apace, with refinements in microprocessor control and other developments enhancing performance. Nearly 100 HVDC systems, including many in North America, are now in service around the world. The largest, in Brazil, is rated at 600 kV.

According to ABB, a key supplier of HVDC systems, newer designs have expanded the power range, extending the economical power range of HVDC systems from 90 megawatts to 1 gigawatt.

High-voltage direct current (HVDC) transmission, continued

Figure 2. HVDC thyristor valves

Photo courtesy of ABB

Figure 3. Intermountain HVDC transmission

The Los Angeles Department of Water and Power (LADWP) operates an HVDC transmission system that brings power from a coal-fired plant in Utah to California.

Map and photo courtesy of ABB

HVDC applications

HVDC can be more economical and more reliable for certain long-distance transmission needs, depending on multiple factors, as outlined in **Table 1**.[3]

HVDC can be the most economical option in some cases. Depending on the distances involved, an overhead DC transmission line and towers may be less expensive per unit of length than an overhead AC line. Although DC converter stations are more costly than AC line terminating stations, in some cases transmission lengths as low as 400 miles are sufficient to make the DC system more economical. The "breakeven" distance needed for economical deployment of HVDC may be less when submarine or underground cable transmission is involved. In these cases, AC cable transmission can be no longer than about 30 miles, but distances of 180 miles have been achieved with HVDC cables, and systems covering over 700 miles are in planning stages.

HVDC cables may make it easier and more economical to site high-voltage lines. Although power demand in certain areas may increase, installing high-voltage lines, or power plants near load centers, typically meets with public opposition. Using compact HVDC underground cables as city infeeds from remote areas may be a means to overcome political problems associated with building such new systems. Moreover, in some circumstances, by upgrading or replacing existing AC transmission lines with HVDC, the power transfer capability of existing rights of way may be substantially increased.

Greater power flow control may be afforded to marketers and system operators. Various restructuring and deregulation schemes have forced the power system to operate in ways for which it was not designed. The power system was, in effect, "designed to operate as a private toll road, and is now expected to operate as an open access highway, handling millions of transactions daily."[4] AC networks do not easily accommodate desired power flow control for today's system, so power marketers and system operators may require the power flow control capability provided by HVDC transmission.

High-voltage direct current (HVDC) transmission, continued

Table 1. Comparison of high voltage AC vs. DC solutions

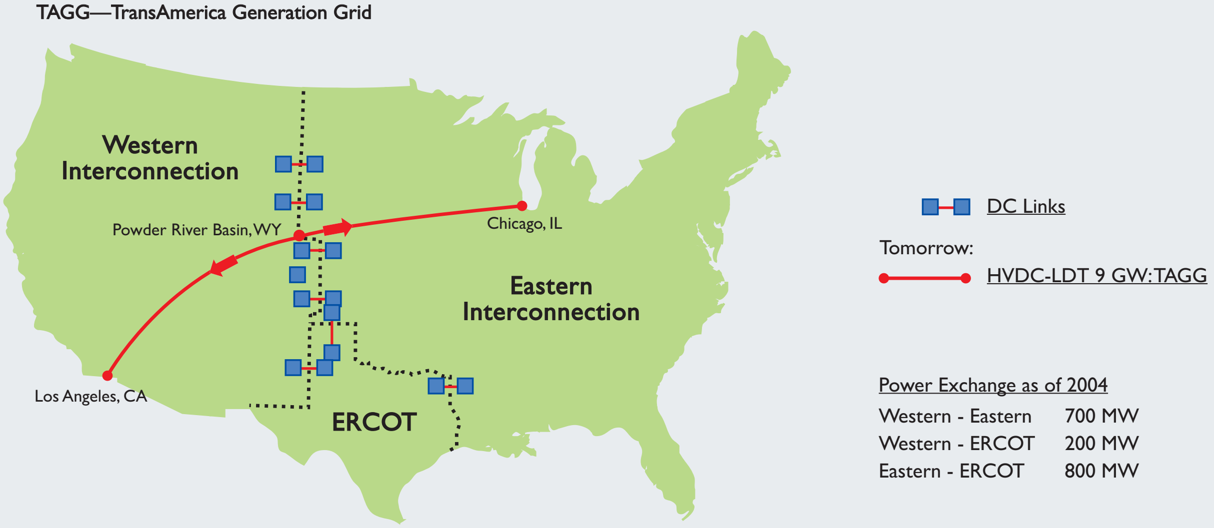
AC solutions work best when:	Consider conversion to HVDC when:
Lines are short and close to thermal rating	Lines are very long and well below thermal rating
Moderate boosts in capacity are sufficient	Very large boosts in capacity are needed
New AC lines can be built quickly and cheaply	New line construction is costly and time consuming
Dynamic conditions require synchronous ties	Systems are weekly synchronized and could benefit from segmentation

Source: I Mod, Inc.[5]

HVDC may be the only feasible means of interconnecting power networks. HVDC can interconnect two separate electrical networks so power can be exchanged between them. Two AC systems can be connected by installing a DC converter station in each system, with an interconnecting DC link between them, so it is possible to transfer power even though the AC systems so connected remain asynchronous. For instance, an AC electric power system may not be synchronized to neighboring networks even though the physical distance between them is quite small. This is the case in Japan, which has asynchronous networks: half the country is served by a 60 hertz (Hz) network and the other half by a 50 Hz system. It is physically impossible to connect the two together by direct AC methods—only DC works.

HVDC can be a barrier to cascading blackouts. Perhaps one of the most vivid examples of a benefit of HVDC is related to its effect on grid reliability. HVDC lines cannot be overloaded and power flow can be controlled for grid stability. This was illustrated during the Northeast Blackout of 2003 blackout, when the Quebec/Canada grid was unaffected, since it is interconnected to the neighboring system with HVDC. As a result, more HVDC interconnections between asynchronous networks such as those in eastern and western U.S. and Texas have been advocated. Additional HVDC links are being considered, most notably the TransAmerica Generation Grid (TAGG), a connection of the eastern and western networks.

Figure 4. U.S. grid areas and DC energy bridges



Power Exchange as of 2004

Western - Eastern	700 MW
Western - ERCOT	200 MW
Eastern - ERCOT	800 MW

Three separate power systems exist in the U.S. HVDC links in the system enable power exchange, and further extensions of interconnections using DC are being considered. (Based on map from "Role of HVDC and FACTS in Future Power Systems," CEPSI 2004 Shanghai paper by W. Breuer, et. al.)

Powering Equipment and Appliances with DC

Many energy-consuming devices and appliances operate internally on DC power, in part because DC can be precisely regulated for sensitive components. An increasing number of devices consume DC, including computers, lighting ballasts, televisions, and set top boxes. Moreover, if motors for heating, ventilating, and air conditioning (HVAC) are operated by variable frequency drives (VFD), which have internal DC buses, then HVAC systems that use VFDs could operate on DC power. Numerous portable devices like cell phones and PDAs also require an AC-DC adapter. As discussed above, by some estimates the AC-DC conversions for these devices waste up to 20% of the total power consumed.

Equipment compatibility

EPRI Solutions examined the compatibility of some common devices with DC power delivery in 2002:[6]

- switched mode power supplies, including those for computers (lab test)
- fluorescent lighting with electronic ballasts
- compact fluorescent lamps (lab test)
- electric baseboard and water heating units
- uninterruptible power supplies (UPS)
- adjustable speed motor drives

These devices represent a large percentage of the electric load, and EPRI Solutions' preliminary assessments show that each could be potentially powered by a DC supply. Although additional testing is needed to determine the effect of DC power on the long-term operation of such equipment, results do indicate the feasibility of delivering DC power to these devices.

Switched-mode power supply (SMPS)

Switched-mode power supply (SMPS) technology is used to convert AC 120 V/60 Hz into the DC power used internally by many electronic devices. At the most basic level, an SMPS is a high frequency DC-DC converter.

Many opportunities exist to use DC power with SMPS-equipped equipment since SMPS technology is found in many electronic devices including desktop computers, laptop computers with power adapters (see **Figure 5**), fluorescent lighting ballasts, television sets, fax machines, photocopiers, and video equipment. Although AC input voltage is specified for most of the electronic devices that have SMPS, in some cases, this equipment can operate with DC power without any modification whatsoever. Also, in many instances, the location on the SMPS where AC is normally fed could be replaced with DC.

Power supplies for desktop and laptop units

According to research on power supply efficiency sponsored by the U.S. Environmental Protection Agency and the California Energy Commission,[7] as of 2004, there were nearly 2.5 billion electrical products containing power supplies in use in the U.S., with about 400 to 500 million new power supplies sold each year.

The total amount of electricity that flowed through these power supplies in 2004 was more than 207 billion kWh, or about 6% of the national electric bill. Researchers determined that more efficient designs could save an expected 15 to 20% of

Figure 5. SMPS unit for Dell laptop

that energy. That amount represents 32 billion kWh/year, or a savings of $2.5 billion. If powered by DC, conversion losses could be reduced and significant savings achieved.

EPRI Solutions conducted tests to assess the ability of two standard SMPS-type computer power supplies to operate on DC; a 250 watt ATX type typically used for desktop computers, and a portable plug-in power module for laptop computers. In both cases, tests revealed that the power supplies would operate properly when supplied with DC power of the right magnitude, although no tests were done to determine power supply operation and performance when connected to the computer loads.

For the desktop computer power supply, sufficient output was provided when supplied with 150 V of DC or greater. For the laptop SMPS unit, 30 V DC was required to “turn on” the output, which begins at 19.79 V and continues at that output unless DC supply drops to 20 volts DC or below.

Fluorescent lighting with electronic ballasts

The key to DC operation of fluorescent lights lies in the use of electronic ballasts. The ballast is used to initiate discharge and regulate current flow in the lamp. Modern electronic ballasts function in much the same manner as a switched-mode power supply thus making it potentially possible to operate them from a DC supply.

Virtually all new office lighting systems use electronic ballasts, which are more efficient and capable of powering various lights at lower costs. Only older installations are likely to have the less-efficient magnetic ballasts in place.

For electronically ballasted applications, several manufacturers make ballasts rated for DC. Lighting systems could be retrofitted with DC-rated ballast units for DC operation. All light switches and upstream protection in line with DC current flow would also need to be rated for DC.

Compact fluorescent lamps

Compact fluorescent lamps (CFL) are energy-efficient alternatives to the common incandescent bulb. A new 20-watt compact fluorescent lamp gives the same light output as a standard 75-watt incandescent light bulb, and also offers an average operating life 6 to 10 times longer.

A compact fluorescent lamp has two parts: a small, folded gas-filled tube and a built-in electronic ballast. As with the fluorescent tubes used in commercial lighting, the electronic ballast enables DC operation of CFLs. EPRI Solutions’ testing of a 20-watt CFL unit with DC power supply revealed that while the CFL could operate on DC power (see **Figure 6**), it required a much higher DC input voltage. With AC supply, the CFL provided constant light at 63 V, but with DC supply, 164.4 V DC was required.

After speaking with CFL manufacturers, EPRI Solutions researchers determined that the CFL used a voltage doubling circuit on the input to the electronic ballast. However, the voltage doubling circuit does not operate on DC voltage. Hence, the DC voltage must be twice the magnitude of the AC voltage to compensate for the non-functioning doubling circuit. This resulting overvoltage on the capacitors could result in shortened lamp life, depending on the ratings of certain input elements in the circuit.

Figure 6. Compact fluorescent lamp running on DC power

Tests showed that some modifications may be required in CFL units for operation on DC power.

The reduction in lamp life is unknown. Additional research is needed to determine whether the energy savings over the life of the lamp would compensate for the increased cost due to premature lamp failure.

Electric baseboard and water heating

DC voltage can be used to run almost any device utilizing an electric heating element, including resistive baseboard and electric water heaters. In these applications, electrical current flowing in a heating element produces heat due to resistance.

The chief concern of using DC in such applications is not in the heating element itself, but in the contactors, switches, and circuit breakers used for such circuits. Since DC is more difficult to interrupt, the interrupting devices must be capable of clearing any faults that develop. There are no DC equivalents to ground fault circuit interrupters (GFCIs), which are commonplace electrical devices used in AC systems to prevent electric shock.

Uninterruptible Power Systems

Uninterruptible power systems (UPS) are excellent candidates for DC power support. A UPS is composed of an inverter, a high-speed static switch, various controls, and battery energy storage. The functional objective of the UPS is to provide high reliability and power quality for connected loads that may be susceptible to voltage sags or short duration power interruptions. Most UPS systems have anywhere from a few minutes up to about 30 minutes of battery storage. For larger UPS units (>30 kVA), it is typical to have a backup generator that starts and picks up load a few minutes after the utility power is interrupted, which, today, is lower cost than having several hours of battery energy storage onsite.

Since a UPS has an inverter and an internal DC bus, it already has many of the elements needed to operate with DC energy.

Variable speed motors

Motors are very important electrical devices, and represent a significant portion of power use in the U.S. In industry, for instance, approximately two-thirds of the electricity use is attributable to motors.

Most AC motor loads still use the same basic technology as the Tesla induction motor. These omnipresent motors convert AC power for applications such as air handling, air compression, refrigeration, air-conditioning, ventilation fans, pumping, machine tools, and more.

A workhorse of modern society, these motors can only operate with AC power. In fact, if subjected to DC power, an AC motor could burn up quickly. In addition, without alternating current, the magnetic vectors produced in the induction motor powered with DC would not be conducive to rotation and the motor would stall—so an induction motor simply will not operate directly on DC power.

But DC can be used if a variable frequency drive is part of the system. A variable frequency drive allows for adjusting the motor speed, rather than operating it either on or off. By varying the frequency of power over a wide range, motor speed can be adjusted to best match the mechanical process, such as circulating air with a fan. This ability to adjust speed can translate into significant energy savings, as a CEO for a major manufacturer explains:

> *And 85% of those motors are electro-mechanically actuated—either they're on or they're off. They're dumb, wasteful motors. If we could convert all of those motors to variable speed, we could cut their [power] consumption by half, which amounts to 10% of total global energy consumption.*
>
> *Imagine if you drove your car with your foot all the way on the gas, then your foot all the way on the brake. You'd get really crappy mileage, and your car wouldn't last as long. Many electric motors work this way: either off or full-speed on. So the motors in most refrigerators, for example, control electricity with a switch— you can hear it go on and off. When it's on, a little motor turns furiously to drive a compressor to cool the refrigerator, then shuts off completely when the temperature falls. That's not efficient. A motor drive that turns exactly*

> *as much as needed is a better solution. It goes a little faster after you open the door, to lower the temperature, then a little slower after it has been closed a while.*
>
> *By varying the speed, a lot of good things happen. For one, you don't have all the energy losses from acceleration and deceleration. Also, you don't need as big a compressor, since it doesn't have to deliver all the energy in such a short period. You can also replace the old-style AC induction motor.*
>
> *—Alex Lidow, CEO, International Rectifier Corp.[8]*

Since a variable frequency drive converts 60 Hz power to DC and then converts the DC to variable frequency AC that is fed to the motor, a DC supply can be readily accommodated, further increasing energy efficiency.

Greater adoption of energy-efficient variable speed motors, now underway for heating, ventilating and air conditioning systems and other applications, represents a greater opportunity for deploying DC power. In addition, several manufacturers now offer DC variable frequency drives for solar-powered water and irrigation pumps.[9]

Figure 7. Examples of small motor drive units (5–50 hp)

Example Application: Data Centers and IT Loads

One of the nearest-term applications for DC power delivery systems is data centers, or "server farms." These facilities are strong candidates for DC power delivery due to: 1) the availability of products that could enable near-term implementation; and 2) an economic imperative to increase energy efficiency and power reliability.

Seeking relief from skyrocketing power density—and costs

A data center may consist of thousands of racks housing multiple servers and computing devices. The density of these servers keeps increasing, wasting power and generating heat with multiple AC to DC conversions. According to the Consortium for Energy Efficient Thermal Management (CEETHERM), an academic/industry partnership:

> *A server farm or data center consists of thousands of racks with multiple computing units. The heat dissipation from a single rack containing such units exceeds 10 kW.*
>
> *Today's typical data center has 1000 racks, occupies 30,000 square feet and requires 10 MW of power for computing infrastructure. A 100,000 square foot data center of the future will require 50 MW of power for the computing infrastructure. The cooling for such a data center will consume an additional 25 MW of power. Such a data center could cost approximately $46 million each year (at the rate of 10¢ per kWh) just to power the services, and $22 million a year to power the cooling. Energy efficiency is the key to containing these costs.*
>
> *—C. Patel, ITHERM 2002, CEETHERM*

In a 2001 survey of 45 data center managers, Primen (EPRI Solutions), found that most data centers had an electrical intensity of about 40–50 watts per square foot.[10] However, respondents anticipated higher power densities, perhaps as high as 150 watts per square foot.

Indeed, the average electric intensity of today's data centers is higher than in 2001. The power requirements cited by CEETHERM illustrate this, as does an anecdote from one data center manager in November 2005:

> *We'd planned for 50 to 70 watts per square foot and we're blowing past those numbers. We'd planned for 20% growth per year [in electricity demand], but we're at 45% growth per year.*
>
> *—Tom Roberts, Director of Data Center Services, Trinity Information Services, Novi, Michigan*

Consortium for Energy Efficient Thermal Management

To address research challenges associated with thermal and energy management of electronics, the Consortium for Energy Efficient Thermal Management (CEETHERM) was initiated in 2002. This collaboration brings together researchers at the Georgia Institute of Technology and the University of Maryland who have been focusing on related problems for many years, working with industry to sponsor research of a pre-competitive nature.

The consortium concentrates on research topics of medium- and long-range interest as identified in discussion with members. Current research emphasizes package- and module-level cooling schemes for next-generation electronic components, compact fuel cell technologies, combined heat and power approaches for energy efficiency, and computational modeling schemes to aid rapid prototyping, design, and optimization. Technical review meetings are held twice a year, on an alternating basis, on the two university campuses.

For more information, visit http://www.me.gatech.edu/CEETHERM/Purpose.html.

Figure 8. Data center rack

Increasing numbers of servers fill multiple racks such as these in data centers, requiring significant amounts of power.

The need to provide more and more power to new blade server technology (**Figure 9**) and other high-density computing devices has made reducing electricity costs a pressing goal within the data center industry. Multiple approaches are under consideration to increase energy efficiency, including a multi-core approach, with cores running at reduced speed, and software that enables managers to run multiple operating system images on a single machine. However, one of the more intriguing options is DC power delivery. In fact, a data-center industry group formed in late 2005 with support from the California Energy Commission through the Lawrence Berkeley National Laboratory is exploring the challenge of determining how DC power delivery systems can reduce energy needs and enhance the performance of data centers.

Figure 9. Blade servers

Blade servers, which consist of units housing multiple, thin, modular electronic circuit boards (the blades) allow for greater processing in less space. These and other high-density equipment are boosting the power needs of data centers.

Photo courtesy of IBM

Headed by the Lawrence Berkeley National Laboratory and implimented by EPRI Solutions and Ecos Consulting, the group has obtained funding from the Public Interest Energy Research (PIER), the California Energy Commission (CEC) and the California Institute for Energy Efficiency (CIEE) for a DC demonstration project at a Sun Microsystems facility in Newark, California. The objectives of the demonstration are to show:

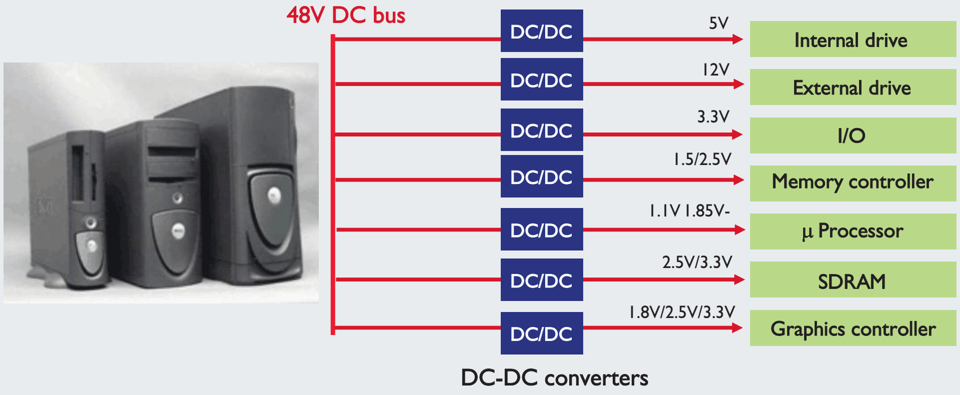
1) How DC-powered servers and server racks can be built and operated from existing components.
2) The level of functionality and computing performance when compared to similarly configured and operated servers and racks containing AC power supplies.
3) Efficiency gains from the elimination of multiple conversion steps in the delivery of DC power to server hardware.

Centralized power architecture

The evolution of centralized power architecture in computers may help standardize and simplify DC power delivery systems serving computer equipment. Separate components within the computer, such as processor, RAM, video card, etc. require different voltages (12 V, 5 V, and even 1.1 V). Computers receive AC power at 120 V and convert it into multiple voltages for these separate internal components. Delivering DC power to today's computers requires providing DC at each of these different voltages. (See **Figure 10**.)

With DC power delivery, one standardized DC voltage—likely 12 V, 24 V, or 48 V—can be accepted at a port in the device, and incorporate point-of-load DC-DC converters at the separate components to adjust the DC voltage as needed.

Figure 10. DC power central architecture for a PC



Distributed power architecture of electronic equipment (example of a personal computer plugged in to a 48V DC outlet.)

Numerous Silicon Valley giants including Intel, Cisco, and others are participating and contributing to the project, including Alindeska Electrical Contractors, Baldwin Technologies, CCG Facility Integration, Cingular Wireless, Dranetz-BMI, Dupont Fabros, EDG2, Inc., EYP Mission Critical, Hewlett-Packard, Liebert Corporation, Morrison Hershfield Corporation, NTT Facilities, Nextek Power, Pentadyne, RTKL, SBC Global, SatCon Power Systems, Square D/Schneider Electric, Sun Microsystems, TDI Power, Universal Electric Corp., and Verizon Wireless.

Potential savings and benefits of DC power delivery in data centers

The existing AC-based powering architecture in a data center, which requires multiple AC-DC-AC conversions, can have an overall system efficiency lower than 50%. How much energy and money could be saved by eliminating these multiple conversions? Field performance data are yet to be documented. However, preliminary estimates of energy savings indicate that about 20% savings could be realized by changing from AC-based powering architecture to DC-based powering architecture for a rack of servers. **Table 2** shows one estimate from EPRI Solutions, which indicates that a typical data center of 1,000 racks could save $3.5 million annually by using a DC power delivery system.

Table 2a. Energy savings estimate for one rack of servers with high-efficiency power conversion

	Total input power (Watts)	Reduction due to air conditioning (Watts)	Total savings (Watts)	Yearly energy savings (MWh)	Yearly energy savings ($)	Net present value (NPV) of savings ($)
AC power*	8,590					
DC power	6,137					
Savings	2,453	837	3,290	28.82	$3,458	$11,984

*The efficiencies for the AC system are based on typical, rather than best-in-class systems. If a best-in-class AC system is compared to a DC best-in-class system, the savings from use of DC power would be reduced. For instance, yearly energy savings might be about $873 rather than $3428. However, gains in reliability from DC power (not shown in this table) would not be achieved.

Only energy-related savings are considered; other savings such as size and heat sink cost not considered. Calculations are based on typical power budget for a dual 2.4 GHz Xeon processor based 1U server rack

1U = TK

Energy cost = 12¢/kWh; project life = 4 years; discount rate = 6%; Overall cooling system efficiency = 1,200 Watts/ton; number of 1U servers per rack = 40

Table 2b. Assumptions

Power conversion efficiency	**AC power architecture**	**DC power architecture**
UPS	85%	N/A
AC/DC PS	72%	N/A
DC/DC VRM (12V – 1.75 V)	84%	84%
DC/DC (48V-12V)	N/A	95%
Nextek power module	N/A	92%
1U dual processor server power budget	**Typical (W)**	**Maximum (W)**
Dual processor power (@1.75V DC)	60	130
Mother board, PCI Card, DDR memory and other peripheral DC power consumption (@12V, 5V, and 3.3V DC)	60	220

To calculate energy savings estimates for different design configurations or using different assumptions, visit an Excel-based calculator, available at the Lawrence Berkeley National Laboratory website (http://hightech.lbl.gov/DC-server-arch-tool.html)

Intel has estimated that power consumption can be reduced by about 10%, and others have projected even higher reductions. Less heat would therefore be generated, lowering the cooling load of the facility. Other benefits of a DC power delivery system are also possible. For example, Baldwin Technologies, which does system design, has promoted benefits of a DC power delivery system for data centers.[12] These estimated benefits are based on vendor claims, rated performance of components, as well as improvements that Baldwin anticipates will derive from its own DC power delivery system design. The benefits and estimated performance improvements include the following:

- A lower number of components are needed, leading to lower maintenance costs and greater reliability.
- DC power distribution delivery is modular and flexible, so systems can grow with load requirements.
- Busways with double end-feed features allow for redundant DC sources at critical loads.
- No down-stream static or transfer switches are required, and voltage-matched DC systems can inherently be coupled together.
- DC distribution eliminates harmonics.
- Grounding is simplified
- Management software and controls are available.
- DC distribution eliminates power factor concern.
- Server reliability may be increased by as much as 27%.

Baldwin's DC power system is being demonstrated at the Pentadyne Power facility in Chatsworth, California (see **Figure 11**), which employs off-the-shelf equipment available from several manufacturers, including:

- **Rectifiers** that convert utility- or generator-supplied AC power to DC (500 VDC)
- **Energy storage**, in this case not batteries, but rather a **flywheel-based system** that can provide power to a 500 VDC bus if AC sources are lost
- **Equipment racks with DC distribution** entailing connectors that enable feeding power from two separate 500 VDC sources for redundancy
- **DC to DC converters** for conversion of 500 VDC power to low-voltage DC (e.g., 48V, 24V, 5 V, etc.) as required by server equipment

Figure 11. Chatsworth facility

Another IT application: Power over the Ethernet

Another information technology (IT) application that may lend itself to DC power delivery is supply for power over the Ethernet (PoE). According to the Institute of Electrical and Electronics Engineers (IEEE):

> *Power over Ethernet technology allows IP [Internet protocol] telephones, wireless LAN [local area network] access points and other appliances to receive power as well as data over LAN cabling without needing to modify the existing Ethernet infrastructure.*

The LAN cables carry both data and power, just as traditional telephone lines carry both voice and power on the same lines. PoE can supply power to computer phones (also known as voice over Internet protocol or VOIP) as well as other devices such as web cameras, electronic badge readers, and even electric guitars or other musical instruments.

The voltage for PoE is 48 V, with about 13 to 15 W of available power at the device. A DC-DC converter transforms the 48V to lower voltages needed for electronics.

The power infrastructure must be able to support the increased power requirements of PoE. In its own white paper on the topic, Cisco Systems states that the overall power budget for both the switch and powered devices is 5,000 to 6,000W. The ultimate source of the power may be AC, but as with the increased power requirements of data centers, facility managers must consider how best to deliver this energy, taking into consideration component costs, efficiencies, and cooling considerations. Cisco notes that its technology can support DC power delivery for the network that is suitable "for installations where highly available power delivery is critical and where an investment in DC power infrastructure is considered to be a business benefit."[13]

Example Application: PV Powered "Hybrid" Building

Ongoing and mounting issues related to energy security, reliability, and emissions reduction make photovoltaic (PV) distributed generation an appealing resource for increased deployment and development. However, costs are still high, despite government rebates such as the "Million Solar Roofs" program in California and federal tax incentives.

For building applications, PV systems typically are supplements to grid power, providing some portion of the load. These systems feature cell arrays that produce DC power, which is converted to AC 60 Hz power for distribution to end-use appliances and equipment.

But the inverter model for PV power system designs has several efficiency penalties and grid connection issues:

Inverter efficiency. Rated inverter efficiencies are between 90% and 95%, representing 5–10% losses, but actual field efficiencies can be even lower.

Reconversion losses. On top of the losses of inverting, additional losses are incurred by converting back to DC in the electronic devices like fluorescent ballasts, computers, and more.

Anti-islanding. For the protection of utility line workers, inverters are required to shut down in the event of grid failure. This means that, for most solar systems, electricity delivery stops during a power failure (when it is likely to be most needed).

Net metering. Power sent back into the grid is not always repurchased at full cost. Sending excess power back into a sometimes overburdened grid may not be the best way to manage the resource. Net-metering agreements and the meters that they require can be expensive.

One solution is to couple a DC power delivery system with equipment such as DC-powered lighting ballasts. A few DC-ready products are commercially available, as noted previously. For instance, the Nextek system, featured in the case study of a distribution warehouse in Rochester, NY on p.20 consists of a special controller/conditioner with an AC power port and a DC input. The controller combines as much PV DC power into the mix as is available or needed to power the lighting system. If more DC power is needed than is available, some grid power can be converted to DC to supplement the local PV source. Like a hybrid car, the "hybrid" building uses two forms of power.

DC power delivery to optimize PV system economics

To evaluate the economics of a PV-DC system, consider the cost components of conventional PV systems employing an inverter. The current lifecycle cost of PV system energy is in the range of 20–40 cents per kilowatt-hour, based on capital costs of PV systems without energy storage in the range of $5 to $10 per watt-AC of capacity. These costs include the PV modules, inverter, AC interconnection equipment, and installation.

The inverters and equipment associated with AC power system interconnection represent 25% or more of the total system capital cost. In addition, inverters may have a life of only 5–10 years prior to needing replacement or significant repair.

Direct current applications of PV can avoid the need for inverters (and inverter repairs) and associated AC interconnection equipment. This could reduce cost, improve reliability, and increase usable power output since the rated inverter losses of 5–10% are avoided. A DC application can also avoid the need for sometimes costly and time-consuming AC interconnection reviews since DC installations are not able to feed AC power back into the utility distribution system. Furthermore, a DC system can continue operating during a grid outage.

Of course, not all PV-DC applications are suitable or can result in lower cost. Careful matching of load and source are needed. For example, by confining a PV system to a single DC load, the advantage of the diverse loads found on the AC system are lost and it becomes more critical that the PV system size and output cycle be optimally matched to end-use requirements. Too large a PV panel on a given load could result in underutilization of the PV energy source and actually raise the effective cost of PV energy compared to the AC inverter approach. Furthermore, DC applications won't eliminate the need for some control and conditioning of the PV energy.

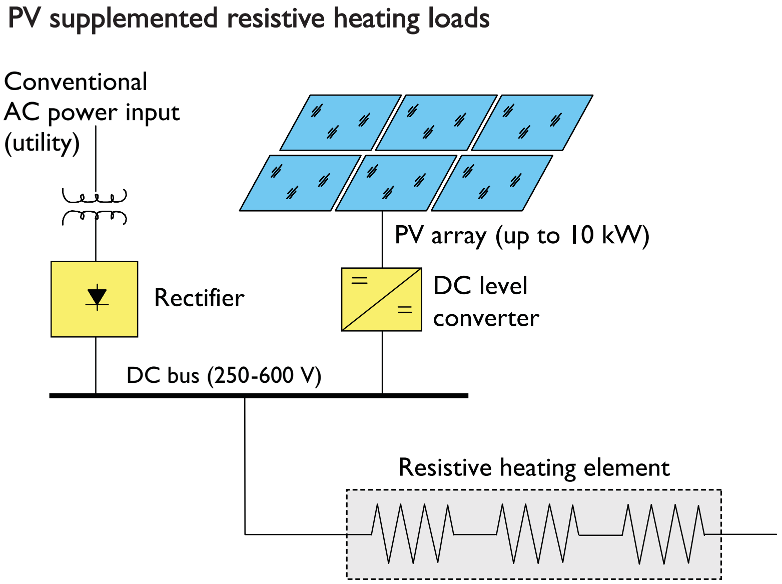
A DC-to-DC voltage converter as well as various load switching controls may be necessary for many PV-DC applications. However, despite these issues, a well-designed PV-DC application can have a significant cost advantage over a conventional inverter approach. This is, in part, because DC-DC converters are more efficient than inverters and can be lower in cost. Furthermore, for some applications, DC-DC converter function can actually be integrated into the end-use equipment, further optimizing the PV-DC approach.

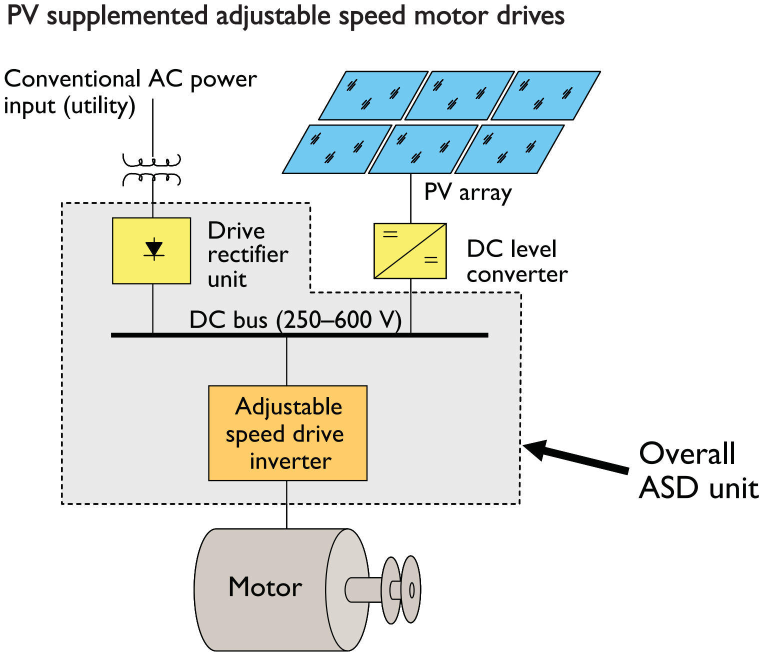
Overall, even though the DC delivery approach comes with some issues, if considering the potential equipment-cost reduction, efficiency enhancements, and value of reducing interconnection concerns, EPRI research indicates that that the total lifecycle cost of PV energy for certain DC applications could be 25% lower than using a conventional inverter approach.[14]

As shown in the section "Powering Equipment and Appliances with DC," many loads can operate with DC power and some are even better suited to DC than AC. These include variable speed motors, lighting technologies, resistive heating elements, and electronic switch-mode power supplies found in various office equipment.

Schematics illustrating how selected AC loads can be supplemented with DC energy from PV are shown in **Figures 12** and **13**. In the applications shown in Figures 12 and 13, 60-Hz utility system power is combined with DC from the solar array on a common DC collector bus. By appropriately controlling the DC voltage level from the solar array (using a DC-DC converter) with respect to the power supplied by the AC system, it is possible to make sure that PV energy is utilized when it is available but that 60-Hz utility power will "pick up" the load entirely if there is no PV power output. To insure full utiliza-

Figures 12 and 13. Two examples of direct current PV energy approaches





In these examples, a heating application and a variable speed motor application, PV power supplements incoming AC power.

A PV-DC case study, distribution warehouse, Rochester, New York

Nextek Power Systems recently designed and installed their high-efficiency renewable energy lighting system at a distribution center in Rochester, New York. This facility is equipped with a lighting system that utilizes DC fluorescent ballasts, roof-integrated solar panels, occupancy sensors, and daylight sensors for high efficiency. The building, including the innovative lighting system, was designed by William McDonough and Partners of Charlottesville, Virginia.

The facility has 6,600 sq ft of office space and 33,000 sq ft of warehouse. The warehouse is equipped with skylights and 21 kW of solar panels bonded to the roof material (SR2001 amorphous panels by Solar Integrated Technologies). A canopy in the office area is equipped with 2.1 kW of Sharp panels.

The power from the solar panels is distributed in three ways:

- 2.2 kW is dedicated to office lighting.
- 11.5 kW powers warehouse lights.
- 11.5 kW not needed by the lighting system is inverted to AC and used elsewhere in the building or sold back to the utility.

The entire system consists of 35 NPS-1000 Power Gateways. These devices take power from the solar panels and send it directly to the lighting without significant losses. Additional power, when needed at night or on cloudy days, is taken from the grid.

In the office, 6 NPS-1000's power 198 T-8, four-foot fluorescent lamps, illuminating most areas at 1.1 watts per square foot. Each of the fixtures is equipped with one high-efficiency DC ballast for every two lamps. Most of the fixtures are controlled by a combination of manual switches, daylight sensors, and occupancy sensors in 13 zones.

Figure 14. Sharp panels—canopy

In the warehouse area 29 NPS-1000's power 158 6-lamp T-8 fixtures. These fixtures have low (2 lamps on), medium (4 lamps on), and high (all 6 lamps on) settings so that they can be dimmed by 3 daylight sensors and 30 occupancy sensors located throughout the area. The goal of the control architecture is to maintain a lighting level of 0.74 watts per square foot, using daylight when available, whenever the area is occupied.

The logic of the lighting system is designed for optimum efficiency. Sources of light and power are prioritized such that:

1. Daylight from the skylights is used.
2. If daylighting is not sufficient and the area is occupied, power from the solar panels is added.
3. If daylight and solar power are not enough, additional power required for lighting is taken from the grid.

Figure 15. Office and warehouse lighting systems use DC power

A PV-DC case study, distribution warehouse, Rochester, New York, continued

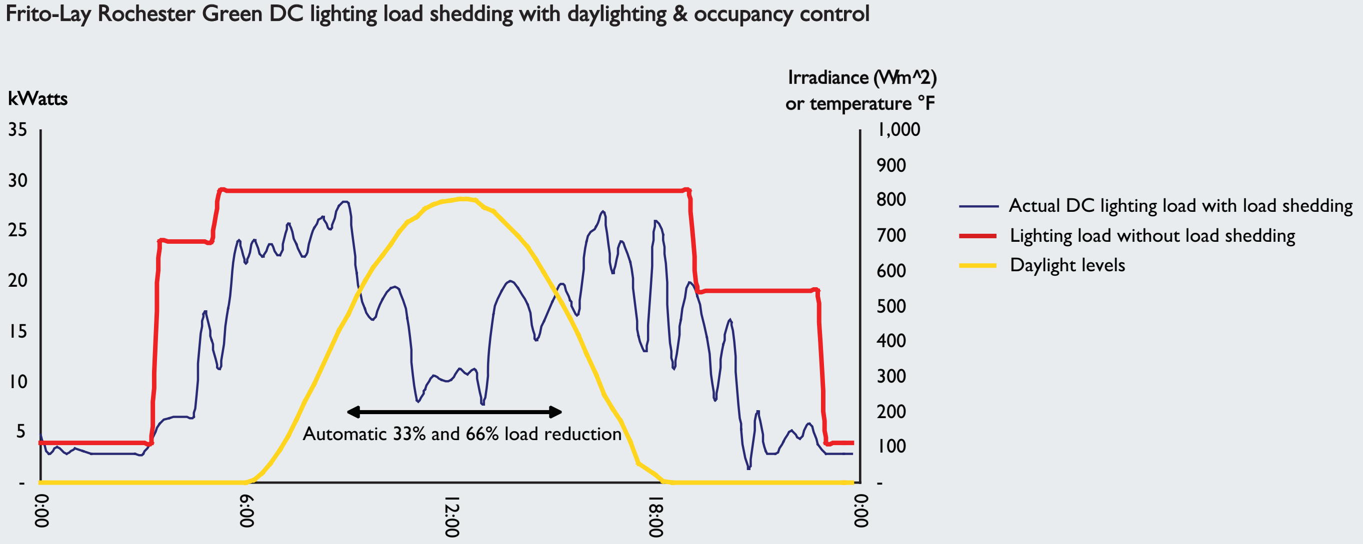
Figure 16. SensorSwitch daylight, occupancy sensors

A number of factors contribute to the value of this system:

- Using the electricity generated by the solar panels to power the lighting eliminated significant inverter losses and improved efficiency by as much as 20%.
- The low-voltage control capability of the DC ballasts enabled the control system to be installed easily, without additional AC wiring.
- Roof-integrated solar panels reduced installation costs and allow the cost of the roof to be recovered using a 5-year accelerated depreciation formula.

Figure 17 illustrates the energy savings due to the daylighting and occupancy controls.

Figure 17. Performance of occupancy and daylight sensors



The red line shows the lighting profile of the building without load shedding. Most of the lighting comes on at 3:00 am. All lights are turned on from 6:00 am to 6:00 pm. The blue line shows the lighting load with the occupancy and daylight sensors controlling the lighting. Between March and mid-June 2005 between 20% and 30% savings were achieved due to the controls.

A PV-DC case study, distribution warehouse, Rochester, New York, continued

Figure 18 shows power from the DC solar system, along with the net utility power consumed by the lighting. Around noon, all of the power for the lighting is supplied by the solar array. An important element here is that the efficiency of solar to lighting is nearly 100%. Only minimal wiring losses are encountered when no grid power is used.

Value

The PV-DC application has been a successful effort for this distribution center, which is dedicated to bringing more "green" and sustainable business practices into its facility operations. The payback on their investment at the Rochester location, after rebates and accelerated depreciation, is approximately 12.6 years, as shown in **Table 3**.

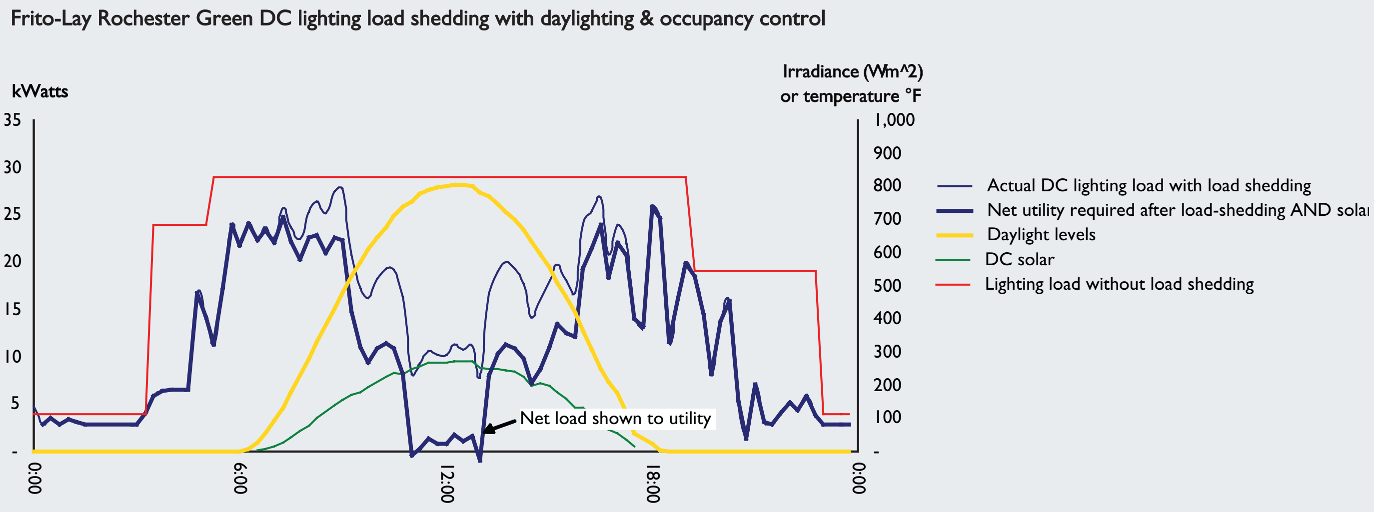
Designers estimate that the system will produce energy for an additional 7.5 years, generating power valued at $60,000 at 2006 electricity rates in Rochester. Note that in areas where the avoided cost of peak power is higher than $0.20 per kWh, the payback on investment can drop to under 6 years, meaning that, the facility would enjoy free peak power from the solar PV array for at least 14 years after the investment is returned. That equates to an $112,000 benefit at today's rates. Either return-scenario grows in value as electricity prices rise.

Table 3. Payback on investment from DC-powered lighting system

System cost after rebate	$72,000
Approximate power savings per year @ $0.10 per kWh	$4,000
Value of system accelerated depreciation, per year, for 5 years, at 30% effective CTR	$4,320
Simple payback	**12.6 years**
If in an area where avoided peak cost is $0.20 per kWh, then simple payback would be 5.84 years	

Data and photographs for this case study courtesy of Nextek Power Systems.

Figure 18. Power consumption by DC lighting system



Example Application: Your Future Neighborhood

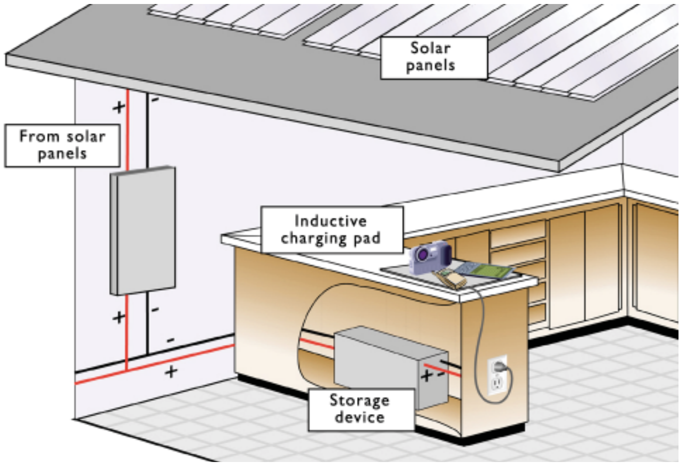
tion of energy without storage, a properly sized PV array would ordinarily produce no more power than the minimum load on the DC bus. Excess power cannot be used because it can't be exported to the AC system.

Adding DC power delivery systems to our homes, office buildings, or commercial facilities offers the potential for improvements in energy-delivery efficiency, reliability, power quality, and cost of operation as compared to traditional power systems. DC power distribution systems may also help overcome constraints in the development of new transmission capacity that are beginning to impact the power industry.

What might a future with DC power delivery look like? A number of options are available. One includes stand-alone systems that can operate full time as off-the-grid "islands," independent of the bulk power supply system. Hybrid buildings are also possible, with utility-supplied power as well as building-based generators such as a solar array, fuel cell, energy storage device, or even a hybrid automobile.

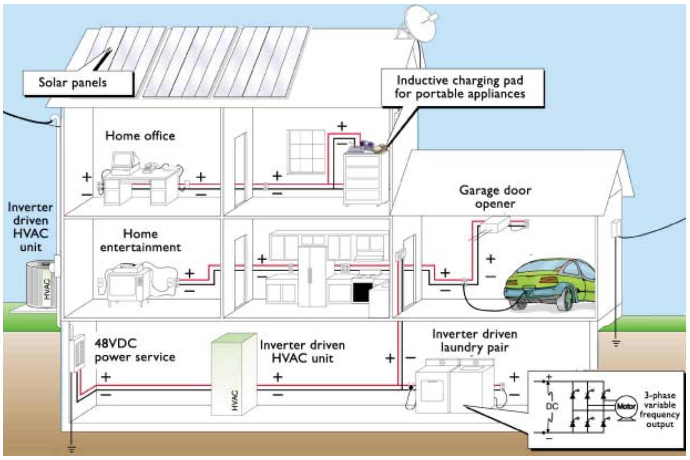
DC systems can operate selected loads or critical subsystems, such as computers and lights. Or a DC charging "rail" such as

Figure 19. A DC-powered inductive charging system



Tomorrow's homes may be blissfully cord free, enabling people to charge portable electronics using an inductive charging pad fed by rooftop solar cells.

Figure 20. A possible DC power system for tomorrow's home



From the kitchen inductive charger to the PC to the air conditioner, appliances throughout the house could be DC powered.

Figure 21. Hybrid vehicles may be able to provide power for the home

Tests have been conducted to enable a hybrid Prius to operate as an emergency home generator and power a home for up to 36 hours. Shown above is a plug that can be used to deliver power into an AC system. DC power delivery options could also be feasible. Moreover, if plug-in hybrids that rely on batteries to a greater extent than today's hybrids enter the market, then charging a car with DC power from a home generator will be possible.

Photo courtesy of EcoTechnology Solutions

Is the DC-powered house a fantasy or could it be a future reality?

Will the "House of Tomorrow" feature DC low-voltage wiring? Instead of relying on the standard AC system with 120V outlets for general use or 240V power for larger loads like air conditioners or ovens, will DC wiring become standard? And will it enable greater efficiency and convenience? Some believe it can and offer arguments that the DC-powered house (or at least a hybrid DC/AC house) can be a future reality.

Consider the electronic equipment and devices in a typical home—in how many places are there inefficient AC-DC conversions?

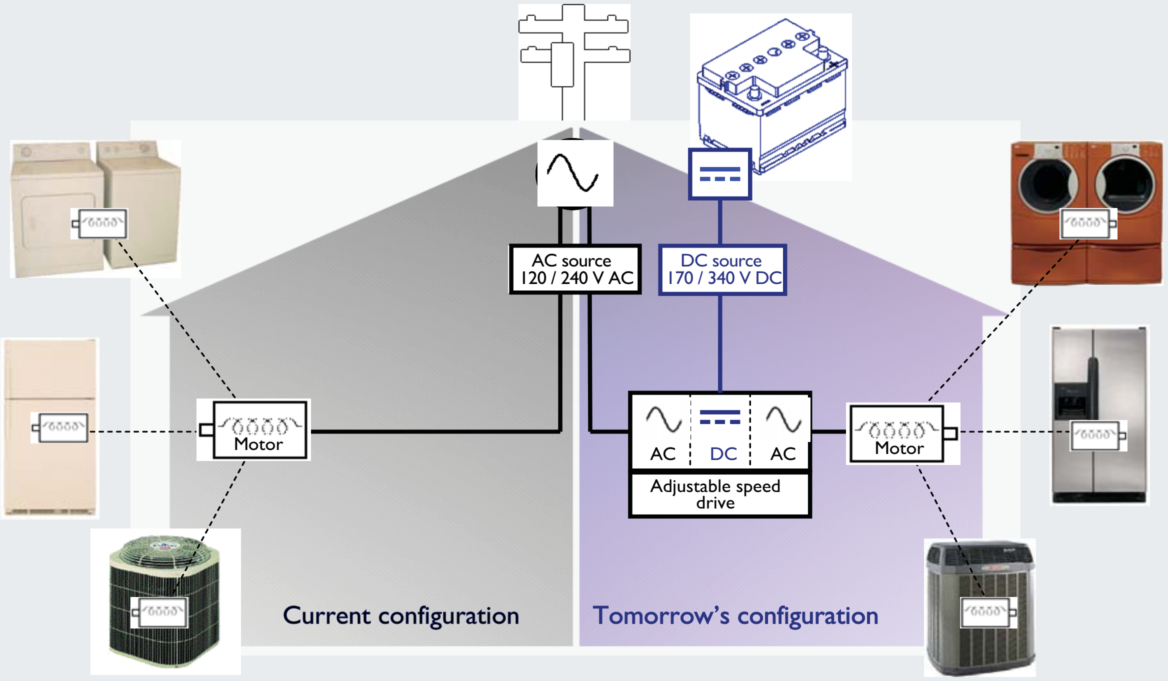
Instead of plugging in your computer at a 120V AC outlet you could plug it in directly to, say, a 48V DC outlet, thus reducing the need for an AC to DC conversion in the computer.

To charge your iPod, personal digital assistants (PDA), cell phone, or the myriad other items that run on DC power, you may have 9V or 12V outlets. The cell phone's microprocessor needs only single-digit DC voltage, so wouldn't it make sense to get it from a DC outlet?

But before getting too carried away with electronics, remember that the bulk of your electricity bill is not for running your computer. "Energy hogs" in the household such as the air conditioner, heat pump, refrigerator and other motor-operated equipment, account for the greatest share of energy consumption. And these motors run on AC.

Are motors a stumbling block for DC power? Not necessarily. In fact, motors could be the ideal load to power with DC. The reason is a revolution in use of motor speed control using electronic variable frequency drives (VFDs). VFDs operate by converting

Figure 22.



The voltage shown here might be 48 V instead. Either 48 V and/or 170/340 V DC could be used. The right DC voltage is a question that is still being addressed by researchers.

Is the DC-powered house a fantasy or could it be a future reality?, continued

AC voltage to DC and then back again to a variable frequency AC, where the frequency is directly related to the speed of the motor. The VFD inherently uses a DC bus, so why not supply it directly with DC instead of AC?

Use of VFDs is on the rise, since controlling the speed of the motor to match demand can not only save energy but also optimize function. For example, being able to fine tune the motor speed of an air conditioner, and thus functions such as fan speed and air flow, can make room temperatures and conditions more comfortable.

As motor-operated loads become increasingly controlled through VFDs –very little will remain in a house that really needs AC power. If both electronics and motors operate on DC—the question becomes just how much can be accomplished by having DC low-voltage wiring in a house? Some opportunities and issues to consider:

- **Energy savings.** If the numerous times AC is converted to DC are reduced, savings of as much as 10% of overall energy consumption are possible.
- **Conversions for varying DC voltages.** Elimination of AC to DC conversions does not obviate the need to convert one DC voltage to another. Various devices and components of appliances rely on different DC voltages. This could remain an obstacle, but an option is to standardize on one DC voltage, as we were able to standardize on 120V AC.
- **Interconnection of onsite generation and storage.** A major, and often overlooked, advantage of DC is the ease of interconnecting generating or energy storage resources. Consider the ease of taking two DC batteries and connecting them together. Then consider trying to do that with two small AC generators from the local hardware store. The Achilles heel of distributed generation is interconnection and integration, which can be overcome with DC power delivery.
- **Onsite generation sources.** Perhaps the biggest advantage of DC powering is that most of the distributed generation and energy storage sources—whether solar panels or fuel cells or microturbines or batteries—are inherently DC sources. You can connect your rooftop solar panel to a home's DC wiring. And when you can finally buy that plug-in hybrid electric vehicle at the local dealership—why not plug that in to your DC outlet? Your car can either be charged—or be run as a generator to power the house.
- **DC power delivery from an Intelligent Universal Transformer.** Your friendly utility may someday provide you with DC power as well as AC, using the EPRI Intelligent Universal Transformer (IUT). The IUT, which is an emerging, revolutionary technology, can directly provide low-voltage DC from the utility
- **Smart home energy management.** As home controls get smarter and digital communication systems advance, we can imagine deployment of an intelligent "gateway" to our house. This central communications and control device could help manage use of all the different power sources (utility power via an IUT, solar panel, batteries, plug-in hybrid electric vehicle) and match them to the load to optimize energy efficiency and comfort. This "Consumer Portal" as it is called by EPRI, could also be the central communications hub for the household, using power lines to carry signals.

The DC-powered home pictured in Figure 20 is still a fantasy. However, technologies are within reach to make it both possible and practical. Changing product designs to eliminate conversion of AC to DC power for electronics and VFDs, and emerging technologies such as plug-in hybrid electric vehicles, the Intelligent Universal Transformer (IUT), and the Consumer Portal could make this picture a reality.

The convergence of technologies may enable us to take generators to where we use electricity—and allow us to seamlessly integrate dispersed generation and renewable resources with the central generation backbone of our electric power system. A DC-powered home could become a component of a network that increases the security, quality, reliability, and affordability of the electric power system. Technology can allow this to happen—your "House of Tomorrow" may indeed be a DC house. Or at least a "House of Tomorrow" where low-voltage AC and DC wiring both are present.

For more information on the Intelligent Universal Transformer, plug-in hybrid vehicles, and the Consumer Portal, visit www.epri.com.

Potential Future Work and Research

the kitchen countertop shown in **Figure 19**, can charge a host of portable appliances.

In fact, equipment throughout the entire house could be powered by DC, as shown in **Figure 20**.

Technology advances suggest that there are significant opportunities for certain DC-based applications, and promising benefits in terms of energy savings and increased reliability. But many obstacles must be overcome. Additional research, development and demonstration are needed to make DC systems viable. Below, we discuss some of the barriers and research needs presented by DC power delivery systems.

The business case for DC power delivery is not yet clear.

Will potential operating cost savings be sufficient to warrant initial capital investment for early adopters? For what applications? To what extent will DC play into new power delivery infrastructure investments? How, for example, can DC power systems enable use of plug-in hybrid vehicles, which may become tomorrow's mobile "mini" power plants? Systems that will accommodate efficient, safe, and reliable power delivery between such vehicles and either energy sources or loads are needed. Whether DC power systems are a practical option must be assessed.

Most equipment is not yet plug ready; demonstrations with manufacturers are called for.

Even though electronic devices ultimately operate on DC, they have been designed with internal conversion systems to change AC to DC, and do not typically have ports for DC power delivery. Although some specific products are available to accept DC power—such as DC fluorescent lighting ballasts, or server rack distribution systems—for most loads, AC 60-Hz power still must be supplied. Since the electronics market is highly competitive and has relatively low profit margins, a compelling business case is necessary before product designers and manufacturers will alter their products and add DC power ports—or make other changes to their equipment. To document potential and expand markets, additional demonstrations are needed with equipment that holds promise for use with DC power delivery, such as variable frequency drives.

For data center applications, more field testing and performance measurement are required.

Several manufacturers have developed components that enable DC power delivery in data centers, including rectifiers, storage systems, DC to DC converters, and rack distribution systems. However, the benefits of DC power delivery, such as energy efficiency, have only been estimated, based on vendor claims and rated performance of various components. Measured data on potential energy savings, as well as other performance metrics such as power reliability and power quality, the lifetime of converters, maintenance needs, and other factors are required.

Safety and protection standards and equipment need to be developed.

Since DC power does not cycle to a current "zero" 120 times per second like 60 Hz AC current does, it is more difficult to interrupt the flow of DC power. Therefore, DC power switches and interrupters employing semiconductors or other technology are needed for DC delivery systems. Also to be addressed are when and where solid state switches need to be applied, and when an air gap is required. Further, techniques for controlling transients, such as spikes from lightning strikes, require additional investigation and testing—as does research for grounding and balancing DC.

Standard practices for design, installation, and maintenance need to be established in the marketplace.

Adoption of any new technology or design procedures can represent a significant hurdle. Designers, technicians, install-

AC vs. DC Power: An Historical Perspective

ers, retailers, buyers, and users want to mitigate risk and cost, which requires investment in product development, system integration, professional training—and time.

Early power systems developed by Thomas Edison generated and delivered direct current (DC). However, DC power systems had many limitations, most notably that power typically could not be practically transmitted beyond a distance of about one mile.

Moreover, because changing the voltage of DC current was extremely inefficient, delivery of power with direct current in Edison's time meant that separate electric lines had to be installed to supply power to appliances and equipment of different voltages, an economically and physically impractical approach. Another limitation was that DC current incurred considerable power losses.

Figure 23.

Edison's Pearl Street Station entered service on September 4, 1882, serving 85 customers with 400 lamps. This early electric distribution system on direct current power delivery which could not extend over about a mile.

Picture Courtesy of Con Ed

Edison's concept for electrification of the U.S.—which included royalties from his patents on direct current systems—was to deploy relatively small scale, individual DC plants to serve small areas—such as the Pearl Street Station (**Figure 23**), which powered a part of New York City's financial district.

But George Westinghouse's polyphase alternating current (AC) power system—invented by Nikola Tesla and used with transformers developed by William Stanley, Jr., who also worked for Westinghouse—proved to be far superior technically and economically. The voltage of AC could be stepped up or decreased to enable long distance power transmission and distribution to end-use equipment.

Edison fought vociferously against the use of alternating current-based systems, which he claimed would be dangerous because of the high voltage at which power would need to be transmitted over long distances.

> *My personal desire would be to prohibit entirely the use of alternating currents. They are unnecessary as they are dangerous.*
>
> *—Thomas Edison, 1889, Scientific American*

He even went so far as to demonstrate the danger of AC by using it to electrocute a Coney Island elephant named Topsy who had killed three men. He also electrocuted numerous cats and dogs procured from neighborhood boys. But despite proving that alternating current could be an effective means of electrocuting these hapless creatures, its superiority to DC for transmission and distribution was compelling.

Alternating current can be produced by large generators, and the voltage of alternating current can be stepped up or down for transmission and delivery. The distance limitation of direct current and the difficulties of changing voltages proved critical factors in abandoning DC systems in favor of those based on AC. With DC systems, power had to be generated close to where it was used. This resulted in problematic reliability and economics. If the local plant failed, the entire system was down. And because initial power systems were devoted to lighting loads and systems only generated power at times of high usage, the cost of energy was high—often more than $1 per kWh when adjusted for inflation to present dollars (2005) —compared to an average cost for residential electricity today of 8.58¢ per kWh.[15]

Engineers wanted to Interconnect systems to improve reliability and overcome the economic limitations of DC electrical systems. If one area's power were out because of a problem at the generator, then the adjacent town would be available to pick up the load. In addition, by interconnecting isolated systems, a greater diversity of load was obtained, which would improve load factor and enable more economical operation of the generation plants.

Another major driver was the desire to make use of hydroelectric power sources located far from urban load centers, which made long distance transmission essential, and therefore made alternating current essential.

Transformers transform the power delivery system

By using transformers, the voltage can be stepped up to high levels so that electricity can be distributed over long distances at low currents, and hence with low losses.

Transformers that could efficiently adjust voltage levels in different parts of the system and help minimize the inherent power losses associated with long-distance distribution were a critical enabling technology that led to today's AC-dominated power distribution system. Transformers do not work with DC power.

Effective transformers were first demonstrated in 1886 by William Stanley of the Westinghouse company. According to the Institute of Electrical and Electronics Engineers (IEEE) History Center,[16] Stanley first demonstrated the potential of transformers to enable AC transmission at Main Street in Great Barrington, Massachusetts:

He demonstrated their ability to both raise and lower voltage by stepping up the 500-volt output of a Siemens generator to 3000-volts, lighting a string of thirty series-connected 100-volt incandescent lamps, and then stepping the voltage back down to 500-volts.

Wires were run from his "central" generating station along Main Street in Great Barrington, fastened to the elm trees that lined that thoroughfare. A total of six step-down transformers were located in the basements of some Main Street buildings to lower the distribution to 100-volts. A total of twenty business establishments were then lighted using incandescent lamps.

Stanley's demonstration of raising the generator voltage to

Figure 24. The first AC generation plant, Ames, Colorado

Electricity produced here in the spring of 1891 was transmitted 2.6 miles over rugged and at times inaccessible terrain to provide power for operating the motor-driven mill at the Gold King Mine. This pioneering demonstration of the practical value of transmitting electrical power was a significant precedent in the United States for much larger plants at Niagara Falls (in 1895) and elsewhere. Electricity at Ames was generated at 3000 volts, 133 Hertz, single-phase AC, by a 100-hp Westinghouse alternator.

Photo courtesy of The Smithsonian

> *3000-volts and then back down again was exactly the same concept as employed in present day power systems where a "generator step-up" transformer is used to raise the system voltage to a very high level for long distance transmission, and then "large substation" transformers are used to lower the voltage to some intermediate level for local distribution.*

Similar alternating current systems that use transformers eventually replaced Thomas Edison's direct current systems. Stanley's installation in Great Barrington was the first such system to include all of the basic features of large electric power systems as they still exist more than one hundred years later.

Centralization dictates AC instead of DC

Other factors led to the preference for AC power transmission instead of DC power delivery —most notably a desire for large-area grids relying on centralized power plant, such as hydro-electric dams. Having a transmission and distribution system that could provide hydro-electricity to cities or to remotely located industries such as gold or silver mines in the Rocky Mountains was also an economic imperative.

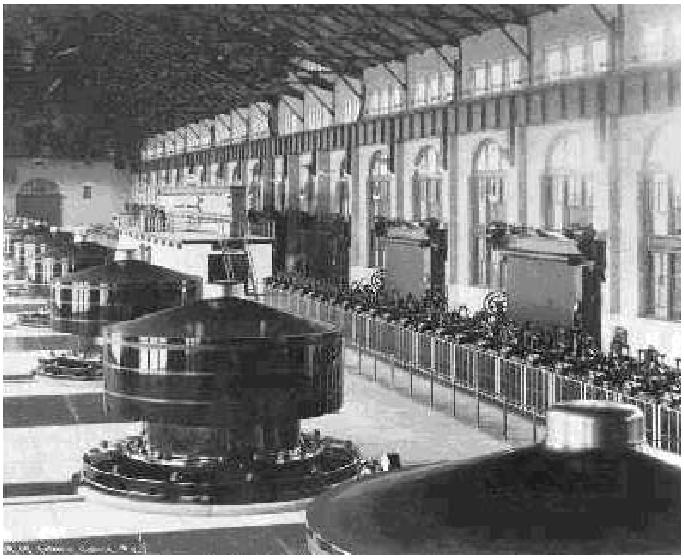
Such development relied not only on transformers, but on development of polyphase alternating current generators. Per IEEE:

> *Niagara Falls represented a showplace of a very different sort. Here electrical engineers were confronted with one of the great technical challenges of the age—how to harness the enormous power latent in Niagara's thundering waters and make it available for useful work. Years of study and heated debate preceded the start-up of the first Niagara Falls Power Station in the summer of 1895, as engineers and financiers argued about whether electricity could be relied on to transmit large amounts of power the 20 miles to Buffalo and, if so, whether it should be direct or alternating current.*
>
> *The success of the giant polyphase alternating current generators made clear the directions that electric power technology would take in the new century.*

In the 25 years following the construction of the Niagara Falls Power Station, various technological innovations and other factors led away from the early small-scale DC systems, and toward systems based upon increasingly larger-scale central-station plants interconnected via transmission lines that carried alternating current. Now cities and towns could be interconnected, and power could be shared between areas. During this period, transmission voltages as high as 150 kV were being introduced, and so relatively large amounts of power could be transmitted efficiently over long distances.

In addition to technical and market forces, the government also played a role in development of centralized power systems and thus reliance on AC transmission. Public policy and legislation

Figure 25. Adams Hydroelectric Plant, 1895



When the Adams Plant went into operation on August 26, 1895, it represented a key victory for alternating-current systems over direct-current. The clear advantage of high voltage AC for long distance power transmission and the unprecedented size of the plant (it reached its full capacity of ten 5,000-HP generators in May 1900) influenced the future of the electrical industry worldwide.

Photo courtesy of The Smithsonian

Notes

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