

COMMERCIAL AND INDUSTRIAL APPLICATIONS GETTING READY FOR DIRECT-CURRENT POWER DISTRIBUTION

Dave Crudele, Tom Key, Arshad Mansoor
EPRI PEAC Corporation
942 Corridor Park Blvd. Knoxville, TN 37932
dcrudele@epri-peac.com, tkey@epri-peac.com, amansoor@epri-peac.com

Faisal Khan
University of Tennessee
Knoxville, TN
fkhan@epri-peac.com

Abstract

This paper describes design trends in several classes of power-electronic appliances that will increase the appeal for distributing dc power in buildings. In the commercial sector information technology (IT) power conversion architectures are moving from multi- to single-voltage supplies, initially 12Vdc and evolving toward 48Vdc. These changes apply to both data processing and internet server equipment. For motor loads, adjustable speed drives (ASDs) are increasingly common in industrial settings as well as modern commercial buildings. Since these motor drives operate with a 200 to 700V dc-link they are good candidates for direct dc power. In fact, drives are also beginning to appear in single-phase residential appliances and offer opportunities for direct integration with dc from photovoltaic systems or fuel cells. This paper reviews basic design considerations and energy savings potential for operating these appliances directly from dc distribution.

1. BACKGROUND

The growing use of switch-mode power supply (SMPS) technology in all kinds of electronic appliances is not a new trend. From personal computers and peripheral equipment to all kinds of audio and video devices, the SMPS is the most common appliance found in many residential and commercial buildings. High-efficiency electronic lighting and adjustable speed HVAC equipment are the prevalent in modern commercial buildings. Increased use of motor drives for both process control and energy savings is common in nearly all industries. All of these appliances convert power from ac to dc prior to use.

Up to now the increased use of dc electronics in ac applications has been integrated into the available and robust ac-power system. The system has stood the task, but not without a cost. Integration problems have included harmonic distortion and interference in the power system and with other appliances. Additionally, the intolerance of electronic equipment to momentary power interruptions and voltage variations or to a few percent unbalance in a three-phase power system has required remedial actions. In fact, integration of dc-electronic appliances into the ac power

system has prompted a multi-billion dollar power conditioning business that has grown steadily for the past 30 to 35 years. And many of the power conditioners also include several ac-dc-ac conversions using power electronics. The emerging technology using SiC is taking the lead in Power electronics Converters which makes it possible to build small size high power converters with enhanced features.

This paper examines the question of what might be gained if more dc distribution were used in the building wiring that serves these electronic appliances. Realizing that many changes in building wiring practices and equipment would have to take place to allow dc distribution, we have not addressed transition issues and costs. Instead, the paper identifies the trends in electronic appliances and points out the potential benefit of employing dc distribution near the point of end use.

2. POTENTIAL FOR DC BUILDING LOADS

Most power system engineers have become accustomed to ac power delivery and end use. Therefore, the number of devices and applications that are suitable to operate on dc power may be underestimated. Examples of equipment that may be ready for dc include:

- Lighting technologies – incandescent lighting and fluorescents using electronic ballasts
- Cooking and heating – including resistive elements and electronic control systems
- Electric motors – including ASDs and dc motors ranging from small appliances to large industrial plant systems.
- Electronic power-supplies found in various consumer appliances, IT, and peripheral office equipment.
- Batteries, flywheels, micro-turbines, wind generators, fuel cells and photovoltaic arrays are all good candidates to form a critical part of a dc power distribution system.
- Battery charging in Electric Cars in near Future. In Automobiles, the standard for the DC system is going towards 42V from 12V. Thereby, the 48V DC system

will be a direct drive for the battery charging of the Hybrid-Electric vehicle.

Clearly the strongest driver for dc applications is power electronics. The concept of a more “digital society” has led to estimates that in the future more than 50% of electric energy will at some point be processed through silicon. Although there is not agreement on exactly what this number is today, it is safe to say that there is a strong trend for more appliances to incorporate power electronics. With this trend of increasing power electronics usage comes more potential for dc distribution.

3. TODAY'S ELECTRONIC POWER SUPPLY

Many modern electronic devices employ SMPS technology to convert readily available 120 volt / 60 hertz ac power into dc power to be used by the device. At the most basic level, a SMPS is a high-frequency dc-dc converter. Typically, ac-dc conversion is desired so a rectifier circuit is added to the input of the power supply. Figure 1 shows a generic switch mode power supply topology. The SMPS operates in the following manner:

1. At the ac connection terminals the 60-Hz ac supply is rectified and fed unfiltered to the chopper.
2. The dc voltage is then fed to a high-frequency chopper regulator circuit.
3. The chopped dc voltage is applied to the primary winding of a transformer.
4. The transformer's secondary voltages are rectified and smoothed to provide the required dc outputs, such as 12, +5, -5, and 3.3Vdc in a computer application.

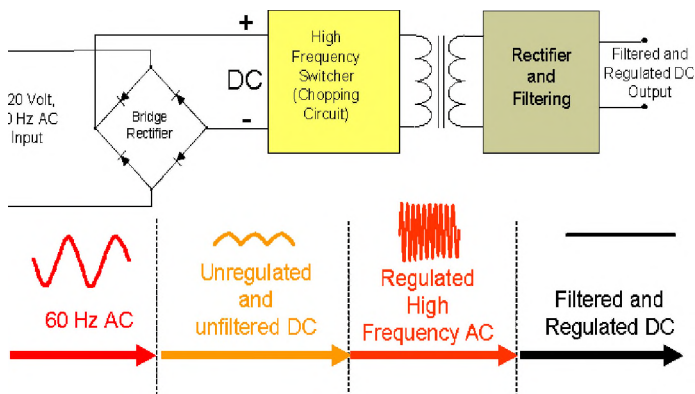


Fig. 1: AC to DC Conversion in a Multi-Output Switch Mode Power Supply

While using 110V ac as the input to the SMPS, capacitors of high voltage rating (at least $1.414 \times 120 = 170V$) are required and there should be a margin of safety to overcome the spikes and transients in the line voltage. While using DC bus of 48 V, capacitors of lower voltage can be used and

evidently capacitors of smaller capacity will be sufficient to get rid of the noise as there will be some central filtering. However, the key point is, the reliability factor (and MTBF) of lower capacity lower voltage capacitors is much higher than the capacitors of higher voltage and capacity. Thereby, the overall system (SMPS) reliability can be increased by using dc voltage as the input. SMPS technology is found in common office electronic devices such as:

- Desktop Computers and Peripherals
- Laptop Computers (power adapters)
- Fluorescent Lighting Ballasts
- Audio and Video Equipment

The devices listed make up a large portion of the electrical load in many commercial facilities. Although the specifications of most of these electronic devices state a requirement for ac input voltage, these devices can, in some cases, actually operate on dc power without any modifications. The problem of providing dc power for today's IT equipment is that there are too many different dc voltage requirements, and some voltage levels are too low for practical power distribution.

4. FUTURE POWER TRENDS IN THE IT INDUSTRY

There are several trends in powering IT equipment that will make dc distribution more appealing. Traditionally desktop computers and low-end server computers have used the multi-output, ac-dc power supply. The different dc levels come from taps off the high-frequency transformer and may be regulated or unregulated. These outputs power the different components including mother board, processor, memory, video card, hard drive, etc. This architecture effectively serves the various requirements from a single power supply placed between the utility and the circuit board.

Microprocessors are increasing their power requirements while reducing logic voltage levels and the traditional multi-output supply is no longer practical. Instead power needs to be converted to the logic voltage at the circuit board level. The Pentium IV, with 1.6Vdc processor, is served with 12Vdc from the supply which is converted to 1.6Vdc at the circuit board by an additional dc-dc conversion. This trend is extending to other components using high-end semiconductors such as the RAM and Video Card processors. On board conversion allows the choice of voltage to optimize the particular function. For example, RAM may need 3.3V and some other device may work better at 2.2V. This approach is shown in Figure 2.

Once a commitment to power conversion at the board-level is made, than a single distribution voltage such as 12Vdc or 48Vdc can be selected. Several manufactures have moved in this direction. The variety of required circuit board

voltages it is becoming almost impossible to apply the multi-output power supply with enough different outputs to meet all the component voltage requirements. Thus the configuration shown in Figure 2 is becoming the norm. It is known in the IT industry as Point-On-Load or POL converters. In addition to allowing better voltage matching at the circuit board, better efficiencies are also claimed.

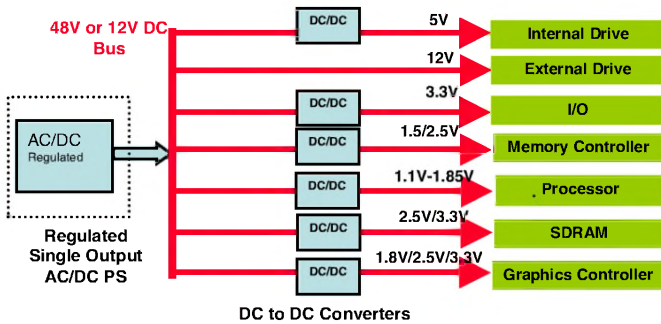


Fig. 2: Schematic Illustration of Power on Load Approach for Powering IT Equipment.

Once complex computer systems standardize on a single input voltage dc distribution between systems can be considered. With a dc power bus in a facility such as a data processing center, other loads including high efficiency lighting can also be powered with dc. Eventually HVAC, lighting and electronic equipment may all be fed from the same dc distribution bus. In this case, other support devices such as battery storage and other dc generation can be added as shown in Figure 3.

Another change that is happening in the IT industry is called Power-Over-LAN. The driving force behind Power-Over-LAN is the wide spread use of CAT5 cabling in offices and homes that are also providing backup power for Voice-Over-Internet (VoIP) applications. The power is used to operate protocol telephony and is already being adapted by many large companies. In this method, two of the Ethernet cable wires are reserved to send power at a dc voltage for equipment such as VoIP telephones. Once the power is available, other products such as WiFi, a personal digital assistant, or something new, can be connected to the internet and powered through the Ethernet cable. Eliminating bulky power supplies for many small devices can provide a big savings in system hardware.

5. TODAY'S ADJUSTABLE SPEED DRIVE APPLICATIONS

An adjustable speed drive allows the user to adjust a motor's speed by varying the frequency of power applied to the motor over a range to better match the speed of the mechanical process. For example, in the case of air

conditioning systems, an ASD can optimize airflow to provide the most efficient system operation – in some cases this can reduce HVAC energy use by well over 10%. ASD units can improve performance so much that it has spurred the creation of a large industry in retrofitting HVAC systems with ASDs and many new HVAC units are incorporating ASDs so that they can be more efficient.

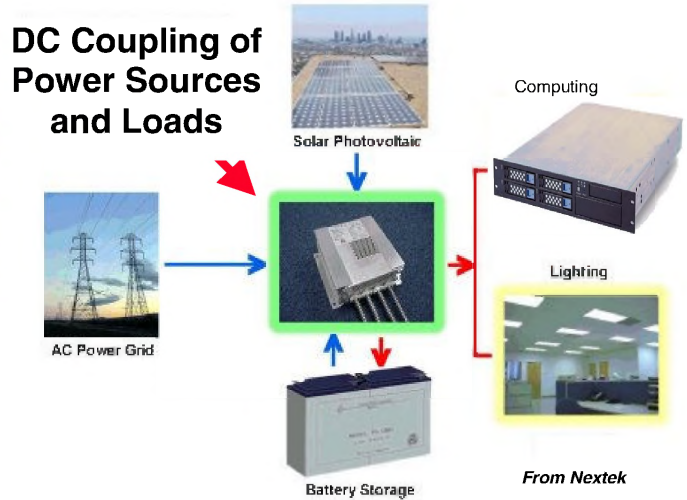


Fig. 3: Schematic Illustration DC Coupling of Multiple Power Sources in Data Processing Application

Electronic ASDs can be categorized into dc and ac motor drives. Ac motor drives controlling squirrel-cage induction motors are the most common types of ASD/motor systems found in industrial and commercial applications. These drives are typically composed of three basic functional blocks: an ac-to-dc converter, a dc link (or dc bus), and a dc-to-ac converter as shown in Figure 4. The ac-to-dc converter may be a controlled or an uncontrolled rectifier. It converts the incoming ac voltages and currents into dc (rectified) voltages and currents. On the dc bus is a capacitor (and possibly an inductor) that filters the output of the rectifier. The dc-to-ac converter or inverter is a set of semiconductor switches that produces ac voltages and currents for controlling the ac motors.

Primarily because of economics and simplicity, most ac motor loads are induction motors. These include applications such as refrigeration, air-conditioning, ventilation fans, water pumping, and machine tools. Traditional induction motors that are connected directly to the ac power system, without an adjustable speed drive, can only operate with ac power. If the induction motors are subjected to dc voltage they will overheat and eventually burn up because motor magnetic core saturates and very low impedance allows high currents to flow. In addition,

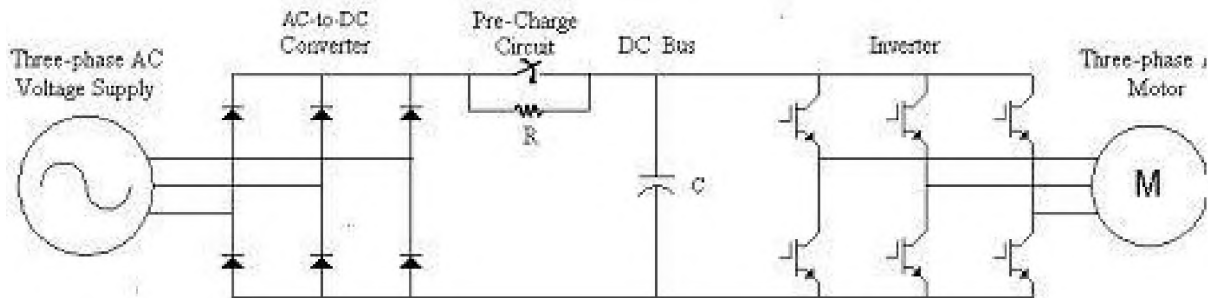


Fig. 4: AC to DC Conversion in an Electronic Adjustable Speed Motor Drive

without alternating current present the induction motor will not rotate.

Given that an induction motor will not operate on dc, it would seem that there is little opportunity for dc powered motor applications. However, the previous discussion illustrates the ease with which an induction motor can operate from an inverter that is driven by a dc supply in an adjustable speed drive. Further discussion in this paper will outline some of the many emerging opportunities for operating induction motors in this fashion. In the near future, variable reluctance motors (VRM) will take over some applications of induction motors because of the simpler construction of it. Eventually, the cost for the construction of motor will go down and there will be a saving in the cost of the entire drive system.

6. TRENDS IN ASD APPLICATIONS FOR SMALL APPLIANCES

The landscape of motor applications (including small appliances) is changing with increasing use of ASD's on the front-end of many traditional motor applications. This change is in part due to the proliferation of increasingly reliable, efficient, and low cost power electronics that are making the use of ASD systems a very desirable option. The worldwide market for electronic motor drives will grow from \$12.5-billion in 2000 to \$19.1-billion in 2005, according to a new market research study by Drives Research Corp. "*Technological advances, government mandates, and globalization are fostering new growth opportunities for electronic motor drives (EMD's) that promise to reverse recent declines in revenue growth rates*" said Thomas Kaporch, President of Drives Research, a market research and management consultant firm specializing in the fields of EMDs and motors.

One of the biggest obstacles to widespread dc powering has been how to power so many different appliances that utilize motors such as refrigerators, air conditioners, clothes washers and dryers, etc. Traditional induction motors, without an adjustable speed drive, can only operate with ac

power. Furthermore, ASDs have historically been too costly to be integrated into most common small appliances.

In the late 1980's and the 1990's, growth in the ASD market was dominated by use of IGBTs. With increasing ASD use in the commercial and industrial sectors, IGBTs became a commodity item. Although there was strong growth in the ASD market, it was not initially accompanied by the IGBT cost reduction necessary to make ASD's appealing for widespread integration with motor driven appliances. In fact, the benefits of reduced cost IGBTs are just now being realized. Coupled with decreasing IGBT prices, the appliance industry is now benefiting from the emergence of drives for brushless dc motors and synchronous reluctance (SR) motors. These drives are already being integrated into high-end appliances using brushless dc motors. It is evident that these advancements in ASD technology are allowing for more economical ASD units which are now being embraced by appliance manufacturers to drive refrigeration compressors, cooling fans, mechanical agitators, and many other motor-driven appliance applications.

Regardless of the type of motor being driven, the ASDs under consideration all utilize a topology that employs a rectifier on the input to the drive. Thus the incoming ac power is converted to dc for use within the drive. As such, this technology lends itself just as well to a dc supply as it does to an ac supply. This fact coupled with the emerging widespread use to ASD technology within common appliances means there is a huge potential market for dc driven applications within the appliance industry.

7. DC IN DISTRIBUTED GENERATION AND STORAGE

Most of the emerging generation and energy storage technologies that are near the point of end use involve a DC power platform. These include:

- Micro turbines
- Small wind turbines
- Fuel cells
- Photovoltaics
- Electrochemical capacitors

- Flywheels
- Traditional and advanced battery energy storage

Micro and small wind turbines operate at variable speed, typically using a permanent magnet alternator and rectified output to dc for practical use. If ac is desired an electronic inverter is added. Modern high-speed flywheel energy storage uses the same technology to capture energy, and as the wheel spins down a dc output is provided. Both photovoltaic and fuel cells generate dc that can be regulated using power electronics. Of course batteries and electrochemical capacitors provide dc and usually require some form of power electronics to provide regulation. Due to the dc nature of these distributed energy resources (DER), there appears to be great synergy between these inherently dc generation and storage technologies and possible dc loads. For example, Figure 5 shows a hypothetical dc distribution system incorporating local generation, energy storage, and loads.

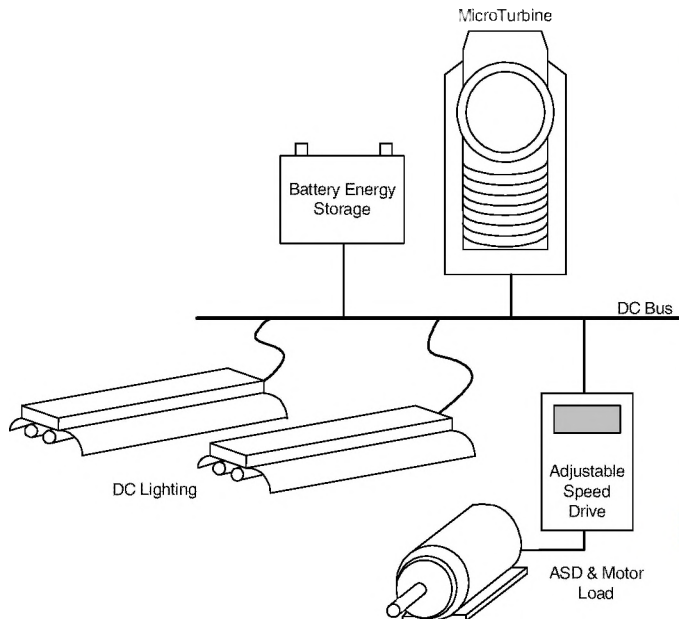


Fig. 5: DC Distribution and Loads Utilizing Micro Turbine Generation and Battery Energy Storage

One advantage of an all dc system is the removal of the inverter that would be necessary with a dc-based DER and ac-based load. Forgoing the use of an inverter in the system allows for potential cost savings and more reliable and efficient system performance. The typical small scale (under 5-kW) power inverter has a realistic operational life of 3-5 years and thus incurs maintenance and/or replacement costs. Additionally, these inverters are typically on the order of 88-94% efficient resulting in increased system losses. An all dc system would still require the use of dc-to-dc converter between the source and the load to regulate the power supply to the load but dc-to-

dc converters are typically more efficient and reliable than their inverter counterparts. A similar advantage of an all dc system is realized when locating energy storage devices near critical loads for reliability and power quality gains. Matching dc DER and loads allows for a more reliable, efficient, and economical system.

Utilizing a dc-based system architecture also has the potential to simplify the integration of many generation sources and energy storage devices into one power system or micro-grid. Utilizing a common dc bus eliminates the need for precise synchronization between the sources (many of which may be inherently dc) and can potentially allow for a much greater number of separate sources to be incorporated into a localized power system. The concept of the multiple source dc power system is shown in Figure 6.

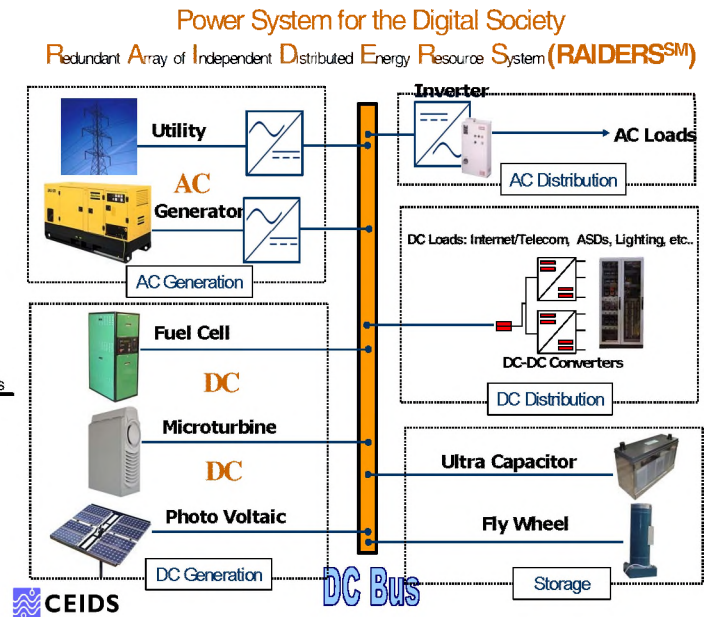


Fig. 6: Potential for Multiple Distributed Energy Resources within a DC Power System

There are several advantages of a common DC bus rather than conventional AC bus:

- It is easier to enhance the capacity of the system by adding additional DC power generating sources like PV, fuel cell, wind turbine and the integration is much easier than the integration in AC bus.
- Ripple management can be accomplished by adding more capacitors in the DC bus.
- System reliability is higher. In AC bus system, if any power generating source like an alternator fails, there is a good chance of circulating current to flow through the alternator and there is a big impact on the system. However, in common DC bus, every power-generating

source can be isolated using diodes and they are able to share the power independently.

8. POWER SYSTEM INTERCONNECTION ISSUES

Distributed generation interconnection is a controversial and complex issue. The methods and approaches that are considered acceptable are still evolving today and will change as the penetration of DER increases on the power system. The beauty of the dc approach is that it can avoid essentially all of the interconnection issues associated with distributed generation.

The issues for traditional ac interconnected DER include the danger of islanding, the potential to cause improper operation of utility system over-current protection devices, the potential to cause damaging over-voltages, interference with voltage regulation systems and degraded power quality and reliability problems. To avoid these issues, DER must have anti-islanding protection, proper relaying for fault conditions protection for abnormal system voltages, low harmonic injection, a proper grounding interface with respect to the utility system and an appropriate means of disconnect from the power system. If the DER is of significant size with respect to the power distribution system load, then it must also be coordinated with the system planning and operation.

While these DER interconnection requirements are appropriate and necessary to avoid safety, power quality, and reliability issues, there is much confusion about how such installations should be approved and what requirements are necessary. Standards such as IEEE 929-2000¹ and IEEE 1547² are helpful and establish guidelines at current levels of DER penetration on the power system. However, interconnecting even a small PV system to the utility grid through an inverter is still a long and complex process at many locations in the country.

Since essentially all of the concerns of utilities stem from a DER ability to inject *fault current contributions and power* into the utility system, a dc approach is an interesting way to prevent such injections. The dc approach is able to avoid almost all of the key complications of interconnection because they isolate the generation from the grid. DC applications are either stand-alone, in which case they have absolutely no impact on the ac power system, or they are parallel with the ac system by means of a blocking diode (rectifier). In the later case, the blocking diode prevents power injection into the ac system during both steady state

and transient system conditions and so there can be no fault contributions, or reverse power injection from the dc system into the ac power system.

The only system impact that might occur is fluctuating output of the DER, for example photovoltaic or wind, causes the ac load to appear to fluctuate at the site. If the PV-dc application was large enough and the load at the site large enough relative to the power system, then voltage fluctuations and the potential for related light flicker might occur.

A worst-case scenario for the dc approach is a failure of the blocking diode used in the dc architecture. This could lead to *dc power injection* into the ac system and this could saturate the nearest upstream transformer (depending on the facility layout, the nearest transformer would be either a low voltage building transformer within the customer premises or the distribution transformer serving the site). This unlikely possibility can be protected against with basic circuit protection approaches similar to those used at millions of UPS sites around the country. The UPS installations around the country already pose this threat and are “interconnected” without stringent requirements and studies.

9. CONCLUSION

Increased use of power electronics, distributed generation and storage are all expected to contribute to dc electrical distribution opportunities. ASD interfaced induction motors, modern appliances, and cutting-edge IT equipment are only a few of many applications that may be served by dc direct power distribution systems. Adjustable speed drives and switched mode power supply technology, designed for use with ac systems, already presents great potential for dc integration with little modification.

The potential advantages of dc distribution include increased energy efficiency, a reduced number of power conversions and harmonic elimination. Furthermore, dc distribution simplifies the integration of distributed generation and allows direct connection to energy storage technologies that can provide uninterruptible power and protection from voltage disturbances. The first applications of dc distribution are expected to be in data processing or internet server facilities. One reason is that computing technologies are already gravitating towards a common dc supply and point-on-load voltage conversion. Another reason is that the application of energy storage for better reliability is highly valued in IT applications.

¹ IEEE 929-2000, Recommended Practice for Utility Interface of Photovoltaic (PV) Systems

² IEEE Standard 1547-2003™ Standard for Interconnecting Distributed Resources with Electric Power Systems