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DC Power - Potential Applications

By Reginald Brown

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CONTENTS

FIGURES

TABLES

1 INTRODUCTION

Recent years have seen a rapid growth in the number of items in the home that use direct current (DC). Every purchase of portable consumer electronics, from phone and IT equipment to electric toothbrushes, seems to arrive with yet another plug-top power supply which more than likely cannot be used with anything else. Moreover, that power supply may be left plugged in and consuming electricity whether or not the associated product is attached.

Even in the realm of fixed equipment we now have low voltage lighting, environmental controls and energy efficient DC motors. Despite the fact that power is universally supplied to homes as 230 volts alternating current (AC) there are few appliances that do not internally rectify the incoming power or could not use DC directly if it were available.

At the same time, it is increasingly common for houses to generate a small amount of electricity from photovoltaic (PV) panels. Does it make sense to generate DC power, convert it to AC at 230V and then back to DC with the inefficiencies inherent in each stage of the process? Would it be possible to create a DC power distribution network to use the generated power more directly? These questions are more complex than may first appear since there are issues of voltage matching and import/export or storage to balance supply and demand. Nevertheless, there are sufficient potential benefits for the ideas to be explored through community scale demonstration projects in the UK and elsewhere.

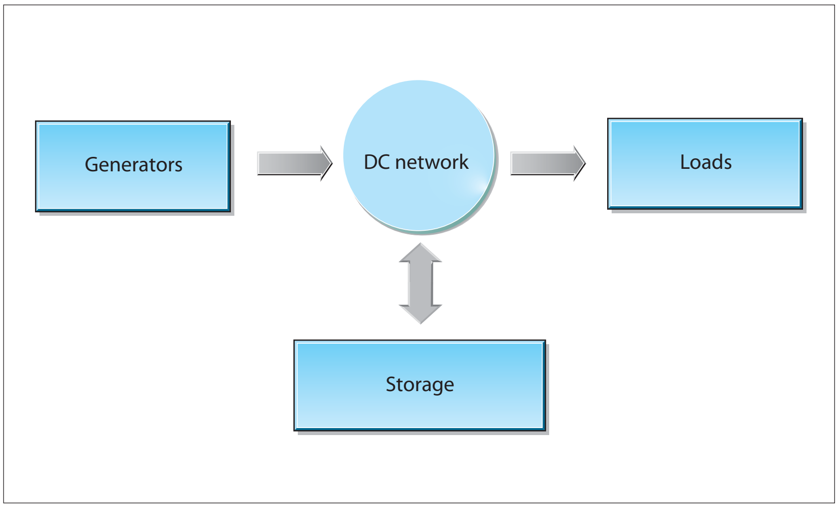
This report discusses the principles, opportunities and challenges for small DC power networks within individual buildings and how the technology may develop in the future.

2 BASIC CONCEPTS

Everyone is familiar with the basic idea of linking a DC source to a DC consumer, for example a battery and a light bulb. It is also easy to grasp the concept of a linking an intermittent energy source such as a photovoltaic (PV) panel to a rechargeable battery and to a load. The issues get more complex when there are multiple energy sources and multiple loads on the same network, all of which must function safely and efficiently when required.

Figure 1 illustrates a simple network concept within a building where a generator supplies power to several loads and also to storage. When the generator is off then the load demand is met by the storage. The storage may be fully floating on the system, but more likely there is an element of charge control to ensure that the voltage provided to the load stays within reasonable limits and the storage device (usually a battery) is not over charged.

Figure 1 : Isolated DC network

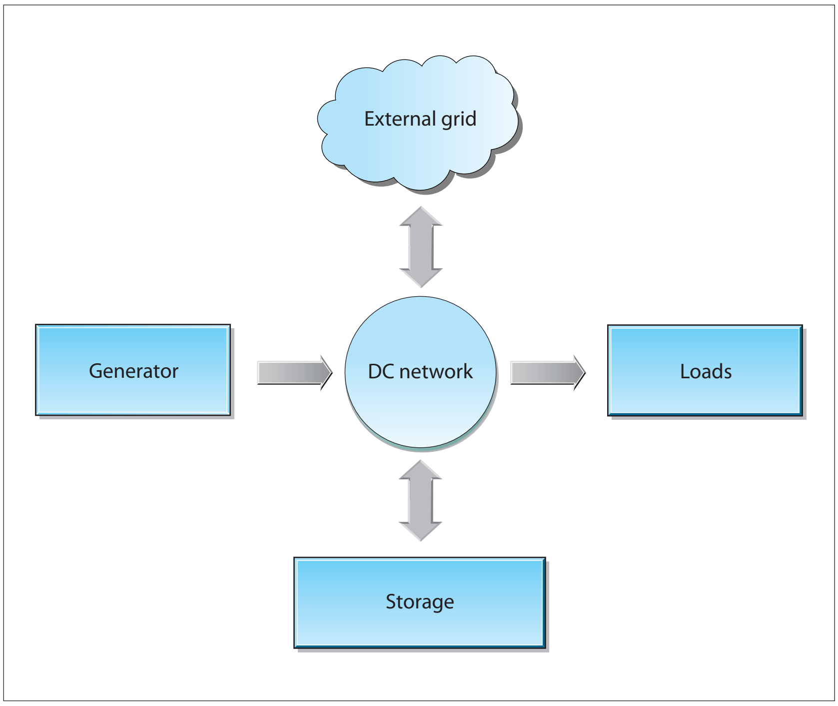


In simple PV systems the charge controller simply blocks excess current or voltage from the PV array to protect the battery. More sophisticated Maximum Power Point Tracking (MPPT) charge controllers (a form of inverter) ensure the maximum power output is achieved from the PV array under all operating conditions while also optimising the battery charging. MPPT controllers can, for example, efficiently connect a 120 V PV array to a 24 V storage and distribution system.

If the generator and storage are not sufficient to cover all the power requirements, as is often the case, there can also be connection to the external grid via a import/export utility meter (see Figure 2). In this system the controller (or possibly several controllers) routes the power in and out of storage and in and out of the (AC or DC) grid. A simple control strategy is to allow power from the grid as a last resort, when the generator plus storage can no longer meet the minimum allowable system voltage (usually determined by the battery cycling characteristics) and to allow export when the loads are satisfied and storage is full. However, that is not the only possible control strategy, particularly if minimum cost operation in association with variable rate tariffs if the major concern. For example it might be reasonable to charge the battery with cheap rate electricity at night.

Of course, most existing building integrated renewable energy and CHP systems work without any storage (since it is not possible to directly store AC power) and therefore rely on the external grid to balance supply and demand. DC systems in the building can also work this way whether with a DC or AC grid connection. The decision about whether to include or exclude storage within the building depends on the evaluation of operating cost benefit and security of supply, one of the major benefits of a DC network within a building being the simplicity of island operation should the external grid fail.

Figure 2 : DC network connected to grid



Some of the configuration features and options that define a DC system are shown in Table 1.

Table 1 : DC network configuration options

Nominal voltage (V)	12, 24, 48, 380, other
Voltage control	fixed, floating, negotiated
Maximum current per outlet (I)	2, 5, 10, other
Line fuses	outlet fusing, plug fusing, electronic
Topology	star, ring, tree (busbar)
Cabling	2 core, 3 core, hybrid data
Grounding and earthing	isolated, grounded, earthed
Storage	battery, electromechanical, other, none
Inputs	grid DC, grid AC, PV, CHP, other
Outputs	lighting, low power applications (<50 W), high power applications (>50 W)
Plugs & sockets	USB, automotive, proprietary

2.1 Nominal voltage

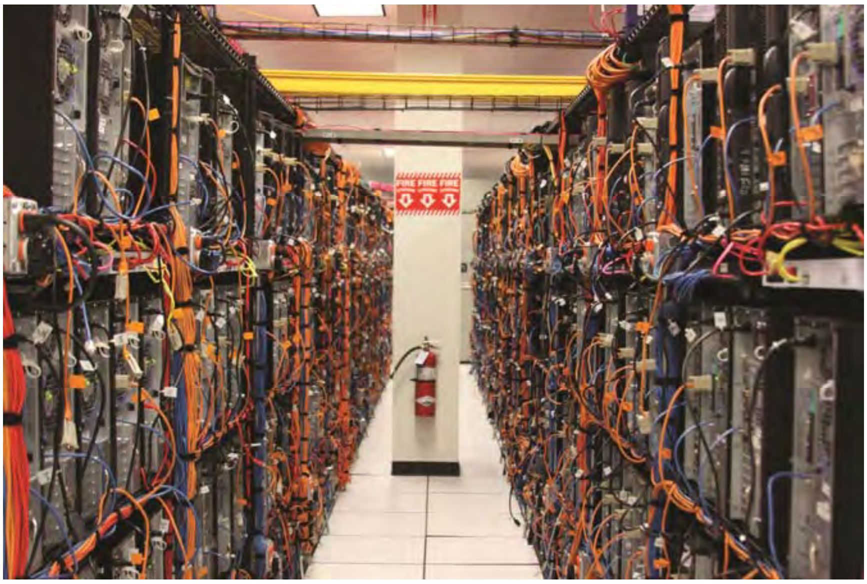
An explanation of these options follows.
12 V is very familiar as the DC voltage used in private vehicles with the ubiquitous 12 volt lead acid battery while 24 V is used in commercial vehicles. A very wide range of circuit components, storage devices and consumer products have been developed for these voltages and are therefore readily available "off the shelf". However, a fundamental characteristic of any electrical system is that halving the voltage doubles the current required for the same power. That leads to thicker cables to reduce the transmission losses.

24 V is therefore more practical than 12 V in terms of power transfer and is potentially more useful with laptop computers and existing DC applications including the developing range of portable battery powered tools and appliances. 24 V is also commonly used for control circuits in commercial buildings.

48 V is currently used in some Power Over Ethernet (POE) and telecoms applications.

There is no fundamental engineering reason why higher voltage DC should not be used subject to the appropriate selection of safety devices and the availability of suitable consumer products to connect to the network. In industry, 380 V DC has been demonstrated for critical services in data centres. Data centres contain a high density of DC loads and are therefore ideal opportunities for DC power distribution.

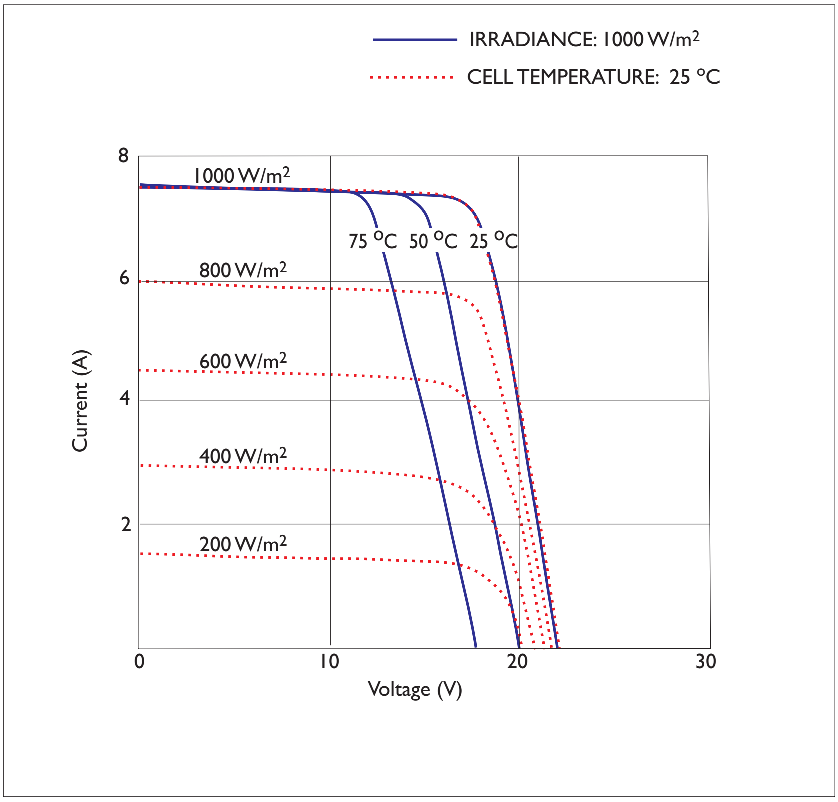
Figure 3 : A traditional data centre



Picture courtesy of The Planet dedicated hosting (www.theplanet.com)

A source can only supply current to a DC network if the voltage of the source is greater than the voltage existing on the network. Therefore, a typical PV array will be engineered to supply 18 V peak for a 12 V system (or possibly 36 V peak for a 24 V system). Figure 4 shows the natural output characteristics of a 12 V panel, which vary according to solar irradiation and temperature. If there is battery storage then the charge controller will keep the actual current and voltage within acceptable limits to avoid boiling the battery on a sunny day.

Figure 4 : Typical 12 volt PV panel characteristic



2.2 VOLTAGE CONTROL

In the existing AC mains culture, users may be only dimly aware that the voltage at the sockets in their house is not actually 240 V. The nominal UK mains voltage is actually 230 V but is allowed to fluctuate by ±6% (13.8 V) on the incoming supply. This means that appliances need to be designed to work properly between 216 V and 244 V. Further voltage drops will occur in the distribution system inside the building and in power and extension leads (if used).

It is possible to operate a DC network in the same way, with relatively small fluctuations in voltage, though it is not necessarily the most efficient or cost-effective approach. For example, in a simple DC system with battery storage, the outlets will operate at the battery voltage. If this voltage is too tightly constrained then the battery will only cycle over a small proportion of its capacity i.e. the nominal storage capacity may be several times the actual storage capacity. Generally, a system with battery storage should cycle over a reasonably large voltage range but ultimately this is constrained by the need to maximise battery life.

Voltage stability can be achieved independently of battery voltage by the use of DC/DC inverter technology but this imposes additional losses.

A related issue is the sensitivity of the loads to voltage fluctuation. Generally it is helpful if loads can operate over a very wide input voltage range but this should not be at the expense of efficiency or the life of the product. Low cost consumer devices may simply waste energy if they are plugged into a socket that provides a higher voltage than needed. Negotiated voltage is used in POE applications. This is where an intelligent load negotiates with the Ethernet switch to provide the voltage requirement within defined current limits. A star topology is used (see section 2.5). This means that different outlets provide different voltages according to the connected load. The outlets have relatively limited power capability (25 W) but are useful for display screens, security cameras, VOIP phones and other devices that can use the IT network without requiring separate power supplies. It is extremely safe as the outlet will not produce any significant voltage or current unless connected to an intelligent device. A similar concept has been proposed specifically for general purpose DC networks that would operate independently of the IT network.

2.3 CURRENT

In any electrical system required to deliver a certain amount of power, halving the voltage doubles the required current. However, with the same cable, the distribution loss due to resistive heating increases by a factor of four (the I^2R loss, a consequence of Ohm's Law). For example, to avoid increased distribution losses and overheating, a cable sized to deliver a maximum of 3 kW at 240 V AC can only deliver 0.3 kW at 24 V DC.

If cables begin to overheat the resistance increases, leading to even more heating and potentially failure or fire. To avoid the risk of overheating, the cross sectional area of the conductor is increased more or less in proportion to the expected current and the maximum safe current is limited by a fuse or circuit breaker. There are other factors to consider such as the thickness of insulation and proximity of other cables that can inhibit heat dissipation. This means more copper and a more expensive cable for lower voltage systems.

The theoretical maximum current available at an outlet (without any fusing) depends on the combination of sources. Where battery storage is used, the maximum current produced under fault conditions, such as a short circuit of a lead acid battery, can be very high, this is sufficient to damage both the cabling and the battery. Short circuiting of a Ni–Cd or lithium battery could result in an explosion.

2.4 FUSES

Protection from overcurrent is provided by a main battery fuse, supply and distribution fuses.

Modern mains power consumer units use miniature circuit breakers (rather than fuse wire) to protect the distribution ring circuit. Additional fuses are fitted in the plug tops for each load. It would be feasible to adopt the same approach for a DC ring network.

Star topologies (see section 2.5) provide fusing of individual outlets at the consumer unit. Since the maximum current available from the outlet under fault condition is lower than for a ring circuit, and the appliance lead can be sized for this, the plug tops don't carry individual fuses.

Miniature Circuit Breakers (MCBs) for DC circuits are readily available. POE systems can dispense with conventional fusing as the current is limited electronically.

2.5 Topology

There are several options for a DC network within houses or other buildings.

Star: each socket is wired directly back to a distribution board with an individual fuse to protect the circuit cabling. This is probably difficult to achieve as a retrofit and involves more cabling than other topologies. Star configuration is also used for POE as described above.

Ring: this is analogous to existing mains power circuits in the UK. Cable size and overall length is reduced by allowing current to flow in both directions around the ring. While there is a fuse for the ring, a smaller fuse is also required at the outlet or plug.

Tree: for short distances it can be convenient to use a single thicker cable or busbar system with multiple outlets. Some 12 V DC lighting systems have connection points on an exposed rail.

Also, having a DC network for some purposes does not necessarily preclude retaining the conventional AC distribution for others. While it is conceivable that some domestic appliances could be operated from a DC network, electric cookers and kettles are unlikely to fall into that category.

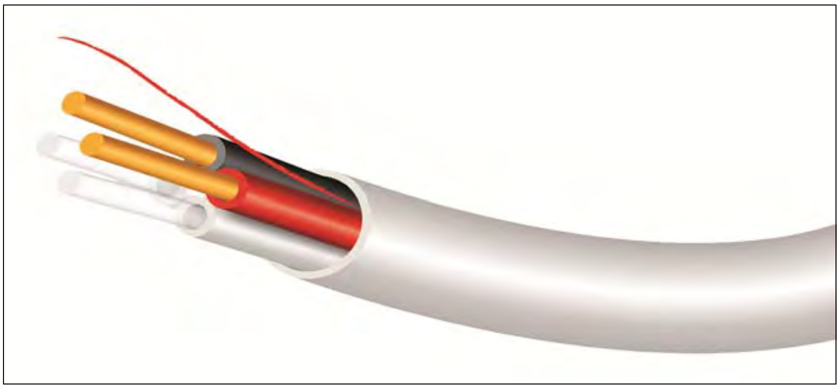
2.6 Cabling

DC power needs a positive and negative conductor, which normally implies a two core cable. Coaxial cables can be used for this purpose. There are some advantages in using multicore cable. A 3-core cable (or 2-core and screen) can provide, say, +12 V, 0 V and -12 V. This allows for powering a 12 V device (by connecting using +12 V or -12 V and 0 V) or a 24 V device by connecting using +12 V and -12 V).

POE is a hybrid system using Cat 5 (obsolescent) or Cat 6 data cable with a spare pair of wires within the cable used to carry power. Power is limited to approximately 25 W per outlet – any higher than this would result in excessive current and voltage drop in the cables.

DC power can also be integrated with fibre optic cabling as shown in Figure 5. This provides 48V over two 0.5 mm diameter solid copper cores, supplying 100W per outlet. The intended applications include computing devices, display screens and internet phones.

Figure 5 : Fibrepoint integrated optical fibre and power cable



Picture courtesy of Fibrepoint Ltd.

2.7 Grounding and Earthing

It is possible, and probably preferable, to operate a DC system that is completely electrically isolated from its surroundings. This is safe, in that touching one wire but not the other cannot result in an electric shock. There is also less risk of electrolytic corrosion due to stray currents.

There are reasons why there might be a relatively high impedance path to “earth” to dissipate any static charge but this is an issue for the designer. This is different from high voltage DC links where the earth itself is used as the current return path.

2.8 Storage

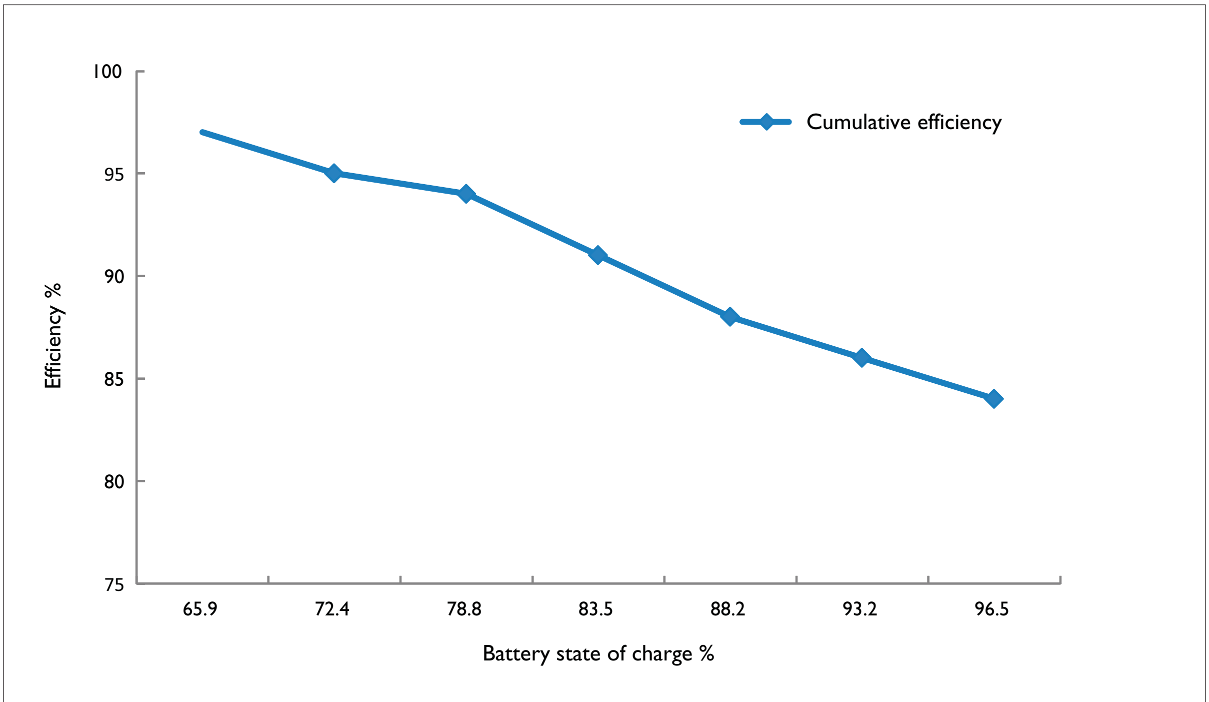
The most feasible method of storage for small systems at present is the electrochemical battery. For stationary storage, the lead acid battery (in various forms) represents the lowest cost solution and can easily be recycled at the end of its life.

Other battery technologies might have operational advantages such as energy density and charging efficiency but are more expensive, potentially hazardous or environmentally questionable. There are also major issues regarding the long term availability and cost of materials used, particularly in lithium batteries.

For any storage battery there is a significant loss of energy in the charge and discharge cycle, particular when charging at near to full capacity. Practical tests on lead acid batteries have shown a charge-discharge efficiency of only 55% when charging from 79 to 84% of capacity.

Figure 6 shows the charging efficiency of a typical lead acid battery drawn from the data of Stevens and Corey. The line shows the average efficiency when charging from flat to the indicated state of charge. Therefore the efficiency when charging from flat to 96.5% of capacity is 84%. Since the charging efficiency declines as the battery gets nearer to full charge, a battery cycling between 80% and 100% of full charge may be charging at only 50% efficiency. It helps to operate the battery at a lower state of charge to maximise charging efficiency but this reduces the effective storage capacity and may reduce battery life.

Figure 6 : Charging efficiency of a typical lead acid battery



Source data: Stevens and Corey

Non-battery storage technologies are discussed in section 6.

2.9 Inputs

There is no reason why a DC network should be limited to use with renewable energy or CHP if it provides benefits when powered from the grid, whether that grid power be AC via an inverter or grid DC.

PV is an obvious DC source for a domestic DC network. CHP (or micro CHP) is slightly less obvious as the systems currently available generally have asynchronous AC generators or alternators intended to work with mains power. Nevertheless, adaptation to a DC network should be straightforward and there may be economic benefits in linking an intermittent source of power such as a Stirling engine CHP (boiler replacement) to a DC storage and distribution network.

2.10 Outputs

The "low hanging fruit" for DC networks in homes is clearly LED lighting and low power (<50 W) applications, particularly those applications that already involve conversion to DC. For televisions and computer equipment it would be desirable to have 250 W per device capability.

Bear in mind that the total circuit capacity must be the sum of the expected loads. A 1 kW circuit operating at 24 V carries 42 amps.

The domestic lighting circuit is interesting as it may present a retrofit option for converting to low voltage LED using existing cabling. Existing lighting circuits use 14 or 18 amp cable.

2.11 Plugs and sockets

The plug and socket arrangement should be distinguished from similar mains power sockets.

24 V DC vehicle plugs are the same as 12 V coaxial fused vehicle plugs and are rated up to 16 A i.e. a 384 W load. This power rating would be sufficient for many low power applications but not domestic appliances.

The Moixa system uses a 12 V USB plug.

The Fibrepoint DC48™ system uses 48 V through RJ50 plugs (backwards compatible with RJ45) providing up to 100 W and can (subject to modification) serve devices intended for POE.

3 COST BENEFIT ANALYSIS FOR DC NETWORKS

Clearly DC networks can be implemented with existing technology but is there a case for doing so and how will this change as the enabling technologies further develop?

There are very good reasons why DC interconnections are likely to become important in the external grid. In particular they provide a mechanism to stabilise and strengthen the local grid in an era of increasingly distributed power generation. The same technology will make it feasible to supply DC and/or AC to consumers from the local substation.

Within a building, particularly a commercial building, there are clearly opportunities to use DC appliances and equipment. The arguments used to date are that firstly there are efficiency benefits in avoiding the use of relatively inefficient AC to DC power conversion for existing DC appliances and secondly there may be some efficiency benefits in replacing some AC equipment with DC equivalents.

An inventory of small power in a typical house would reveal that there are a number of appliances that are internally DC with external power supplies, for example internet hubs and phone chargers. Most such appliances are not in continuous use.

Most usage of external power supplies is occasional and usually associated with battery charging (mobile phone, laptop, camera etc). The problem is that charge control is often a function of the charging device and so use of DC power would require the purchase of another "charger" or interface unit. Overall, any conversion to DC power is likely to require a substantial investment in purpose designed DC appliances. However, that need not be a major problem given that practical DC networks will take some years to develop and roll out, during which time the technology will move on and, in the expectation of a market, there may be little practical difference in the price of AC and DC appliances.

Perhaps the economic argument should hinge not on the additional cost of the appliance but on the additional cost of infrastructure versus the likely benefits of DC versus AC distribution within the building. However, as explained in section 2, there are several choices to be made in a DC network and at present there are no front runners in terms of the system that is likely to be implemented. Moreover, if the system involves DC/DC voltage conversion (up or down), this may introduce inefficiencies that are comparable with those resulting from AC/DC conversion.

In summary:

1. the optimum system will require careful matching of all network components, ideally around a single supply voltage that can be supported by the renewable energy contribution
2. there are specific opportunities for low power DC but in the short to medium term it is likely that dwellings would continue to have access to conventional AC power for larger loads

3. in the longer term it is possible that high power DC appliances will be used (there is a trend in this direction for high efficiency variable speed fans and pumps in HVAC systems) but it then makes sense for the DC to be provided from the local substation

It is possible to calculate some costs for a parallel DC infrastructure for low power applications in a typical house, based on current components and technology. However there is rather limited information about how these actually perform in practice and it is the end to end efficiency that will probably decide the case. Hence the need for demonstration projects.

Moixa quote a figure of £1000-£3000 per house for their 12 V distribution solution but that is rather limited in scope.

In non-residential applications there is slightly more evidence of what can be achieved with basic technology, particularly in data centres. Simply replacing large numbers of individual power supplies with an efficient inverter and DC network is claimed to reduce energy use by 15%. That may not seem much, but data centres are major power consumers and the reduction in heat generation has a knock-on effect on cooling loads.

4 DC NETWORK EXAMPLES

4.1 Bristol study

The Bristol DC network study is a 3 year project which commenced in January 2012, involving Siemens, University of Bath, Bristol City Council, Western Power Distribution and the LCN Fund. This is mainly a technology demonstrator and proof of concept. In essence it provides a DC network incorporating PV and battery storage to power lighting and ICT equipment with a contribution from the grid via an AC/DC (12 V) inverter. Domestic appliances remain connected to the AC grid. It also incorporates "smart appliances"

Figure 7 : Bristol study technical architecture within premises

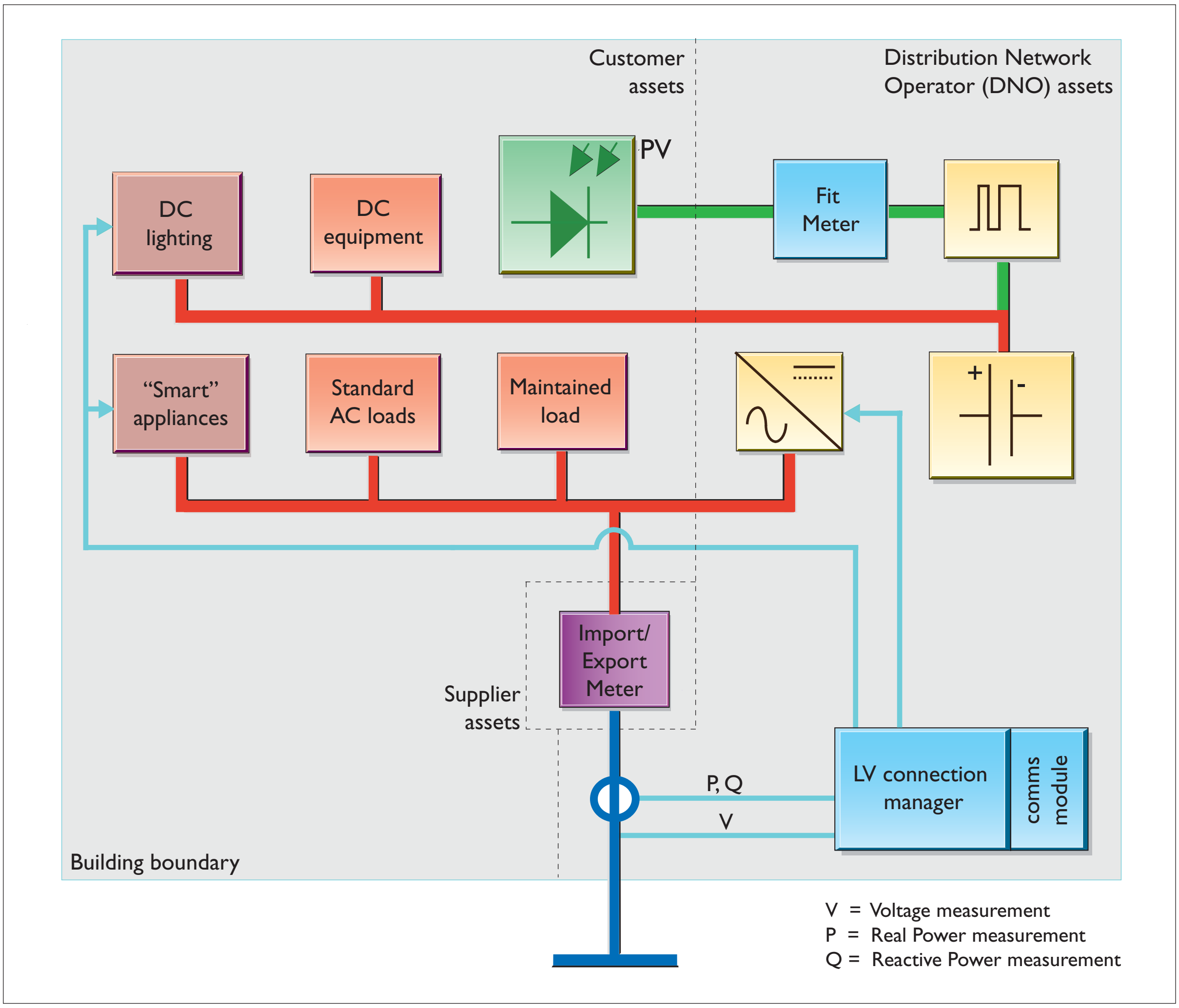


Diagram used with permission of Siemens Infrastructure & Cities.

An interesting feature of the DC distribution system is the involvement of Moixa's 12 V USB variable voltage plug and socket concept that also incorporates energy monitoring.

The overall scheme will include 30 houses, 10 schools and 1 office.

4.2 PROPRIETARY SOLUTIONS

There are already several companies promoting partial DC networks or enabling technologies for specific applications in the home.

Moixa has already been mentioned in the context of the Bristol study and is involved in several other demonstrations. Interestingly they have chosen to market an off-the-shelf home DC network together with optional PV panels and certain DC appliances including lighting components.

Fibrepoint provide a DC power capability with a fibre optic communications network. Access to the DC power is via RJ50 sockets. Although this could be used in the home it is more obviously a commercial building solution.

5 DC SOURCE TECHNOLOGIES

5.1 PHOTOVOLTAICS

The most obvious DC source technology from the renewables perspective is PV. Panels are readily available and costs are falling. PV is currently less attractive than it was due to the reduction of the feed in tariff that took place in December 2011. DC power networks are not incompatible with current or future incentive schemes but these are always likely to be of limited duration. In a 2010 report, PricewaterhouseCoopers (PwC) predicted strong growth in PV installations. It remains to be seen whether this disappears entirely during 2012 in the face of poor economic conditions.

It is estimated from Microgeneration Certification Scheme (MCS) data that by the middle of 2011 there were in excess of 50,000 PV installations in the UK with 5000 installations per month at that time.

The downside of PV (apart from cost) is that not everybody has the opportunity to fit PV panels in an ideal location - south facing without shadows. Line shadows such as those cast by TV aerials, telegraph wires or tree branches are a particular problem and can seriously degrade the performance of crystalline silicon panels.

There are other technologies including PV tiles and large area PV coatings that hold promise for the future. What is clear is that PV is increasingly common and, irrespective of what happens to feed in tariffs, will continue to grow.

5.2 MICRO-CHP AND FUEL CELLS

These are discussed together as both are powered by natural gas and likely to be installed as heat-led systems with electrical outputs of around l kW. Fuel cells are related to batteries and are inherently DC. Micro-CHP is generally asynchronous AC but can be rectified to DC.

At the current state of technology, micro-CHP is just about available in the market - the Baxi Ecogen Stirling engine system is the best known product. Fuel cells are available for demonstration but still far too expensive for routine domestic use.

If the source is heat-led this leads to intermittent operation (the CHP or fuel cell does not run unless there is a heat demand) and therefore intermittent generation of electricity.

It appears that intermittent operation would create a useful synergy with a DC network including battery storage but the problem is that 1 kW is quite a lot of power to input to the sort of battery that might be used in a household system if there are no other active loads. For example, at a system operating voltage, the current would be 42 A. This would be less of a problem for a flywheel storage system.

Overall it seems much more practical to export most of the excess power into the grid than attempt to store it. That does not preclude storing some of the power. The situation is not much better for non-domestic applications since the battery system might be bigger but so is the CHP.

While it would probably not make economic sense to run a natural gas fuel cell solely to provide electricity, this is not the case for a hydrogen fuel cell operating within a theoretical future hydrogen economy where the efficiencies are much higher. A conventional storage battery may still be desirable to use in association with a hydrogen fuel cell as this would buffer peak demands and enable a smaller fuel cell to be specified.

6 DC STORAGE TECHNOLOGIES

Potential storage technologies include various kinds of batteries, supercapacitors and superconducting devices together with non-electrical energy storage such as flywheels, hydrogen gas, pumped hydro and compressed air.

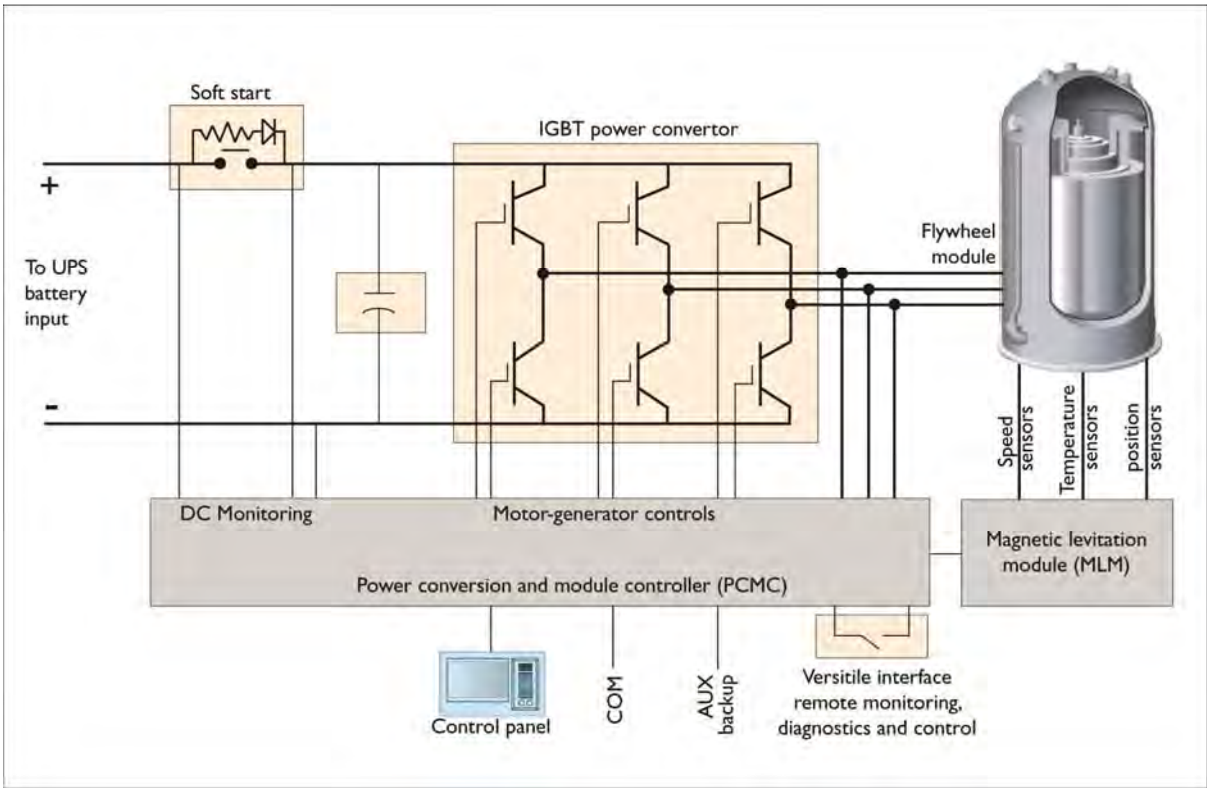
Battery storage solutions have already been discussed. Lead acid technology is relatively cheap and robust, if not particularly efficient. Other battery technologies have issues regarding their cost, use of resources and suitability. However, after a long period of stagnation, battery technology is developing rapidly. A new solution may emerge.

The leading non-battery storage technologies for small DC networks (based on availability and practicality) include supercapacitors and electro-mechanical storage (flywheels).

Supercapacitors have fast charge/discharge characteristics and are used in applications such as the Kinetic Energy Recovery System (KERS) used in some F1 racing cars. Fast charging would not be particularly advantageous in small DC networks while the self-discharge losses would be a major disadvantage. Costs are currently several thousand pounds per kWh but the rate of technical innovation may mean that they are a short-term storage contender for the future.

Flywheels have been around a long time as an alternative to battery UPS for computer systems, and there are now numerous suppliers. Basically, electricity is used in a reversible process to increase the kinetic energy of a high speed rotor in a vacuum canister.

Figure 8 : Flywheel UPS



Source: PowerTHRU™ (www.power-thru.com)

Some characteristics of flywheel energy storage are superior to batteries, for example a 20 year life and fast charge/discharge with high efficiency (>90%). Energy density is also quite good and small units (2.5 kWh) are potentially useful for DC network applications. However, costs are high compared with batteries, and older systems had to be buried in concrete to contain the shrapnel should they fail! Self-discharge rates are also higher than batteries (10% per hour) although not as bad as supercapacitors.

As flywheel energy storage systems are inherently modular, large storage systems can easily be constructed. In 2011 Beacon Power constructed a 100 flywheel system in the US storing 5 MWh with a peak discharge rate of 20 MW. The purpose of this plant is to help regulate grid frequency as conventional power plants go on or off line.

7 POTENTIAL APPLICATION MARKETS

There is little doubt that data centres are the leading market for DC networks at present, for the following reasons:

- Energy and cost savings have been demonstrated simply for switching from multiple to single power supplies for servers and associated devices. There are also knock-on benefits in terms of reduced heat generation leading to lower cooling costs and improved reliability
- The data centre DC power network is relatively easy to implement with a dense concentration of existing DC loads
- Data centres are usually high value operations and operators can afford to invest in new technologies that have demonstrable benefits.

It is likely that technology developed for data centres will filter down to other applications in the commercial office environment (e.g. DC to desk, security and control systems, lighting etc.) and thence to the home.

The home electronics market could not have been predicted 10 years ago. What will happen 10 years from now cannot be predicted in any detail. Some of what is now considered normal will disappear (TV remote controls, laptop computers?) and other technologies will take their place. Such changes will have a major bearing on what DC loads are likely to exist, how they are used and how they are physically connected.

In terms of predicting how we might serve those loads and what solution, if any, may come to dominate the DC network market, the field is still wide open. We have not yet reached the VHS versus Betamax (or Apple versus Microsoft) stage of deciding which path to follow.

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