DC MICROGRIDS: REVIEW AND APPLICATIONS

by

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Abstract

This paper discusses a brief history of electricity, specifically alternating current (AC) and direct current (DC), and how the current standard of AC distribution has been reached. DC power was first produced in 1800, but the shift to AC occurred in the 1880's with the advent of the transformer. Because the decisions for distribution were made over 100 years ago, it could be time to rethink the standards of power distribution.

Compared to traditional AC distribution, DC microgrids are significantly more energy efficient when implemented with distributed generation. Distributed generation, or on-site generation from photovoltaic panels, wind turbines, fuel cells, or microturbines, is more efficient when the power is transmitted by DC. DC generation, paired with the growing DC load profile, increases energy savings by utilizing DC architecture and eliminating wasteful conversions. Energy savings would result from a lower grid strain and more efficient utilization of the utility grid. DC distribution results in a more reliable electrical service due to short transmission distances, high service reliability when paired with on-site generation, and efficient storage.

Occupant safety is a perceived concern with DC microgrids due to the lack of knowledge and familiarity in regards to these systems. However, with proper regulation and design standards, building occupants never encounter voltage higher than 24VDC, which is significantly safer than existing 120VAC in the United States.

DC Microgrids have several disadvantages such as higher initial cost due, in part, to unfamiliarity of the system as well as a general lack of code recognition and efficiency metric recognition leading to difficult certification and code compliance.

Case studies are cited in this paper to demonstrate energy reduction possibilities due to the lack of modeling ability in current energy analysis programs and demonstrated energy savings of approximately 20%.

It was concluded that continued advancement in code development will come from pressure to increase energy efficiency. This pressure, paired with the standardization of a 24VDC plug and socket, will cause substantial increases in DC microgrid usage in the next 10 years.

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Dedication

I dedicate this report to so many: My friends throughout college have surely kept me sane through the process. I have truly felt at home here at Kansas State University in no small part thanks to all of you. And to my parents, Bob and Susie Blasi, whose love and support have been a constant encouragement to seek my dreams. Thank you all.

Chapter 1 - Introduction

Energy efficiency has become a key element in the design and construction industry. Because of increased energy costs over the past several decades and the shift in philosophy to reduce the environmental impact that humans have on the world, it seems that every watt counts.

For many years there has been an ideal that inexpensive energy was the only metric that mattered; it was only the energy bill that owners and operators cared about. As long as it was cheap, no one seemed to mind. However, because of a conscious shift to protect natural resources many people are choosing to pay the premium in order to use renewable resources. Because of the high upfront cost of renewables, designers and owners are attempting to reduce energy usage in order to get the most out of limited resources.

The concept of energy savings has shifted from the load to a global perspective, including the generation source and, distribution efficiency. Considering distribution, the world has a plague of wasteful energy conversions from alternating current to direct current and vice versa.

Instead of increasing conversion efficiency, designers have removed the conversion processes, and utilized a direct current (DC) distribution because of the increasing DC loads in a technologically advanced society.

This paper discusses the background of electricity, how the United States electrical grid came to use 60Hz, alternating current power, and how this standardization would likely not have happened given today's technology. The discussion then briefly introduces DC microgrids, including both advantages and disadvantages. Finally, three case studies are presented, followed by a conclusion and summarization of the paper.

Chapter 2 - A Brief History of Electricity

Has polyphase alternating current (AC) reached its end? This question is best answered by first understanding how AC power became the world standard for electrical distribution.

Alessandro Volta

The origins of human understanding (or attempted understanding) of electricity can be traced to the 17th century; however, prior to 1800, scientists were only able to produce nearly instantaneous current flow. These, high voltage, low current, short duration bursts of electricity were not functionally usable as a source of power.

The first source of electric potential that was not short duration was invented by Alessandro Volta in 1800. Volta was the first to construct what was referred to as a voltaic cell. By using two dissimilar metal disks and placing pieces of brine-soaked cardboard in between them, he created a set of battery cells. These sources were the opposite of previous forms of electricity because; they had relatively low voltage, high current, and were of long duration. This form of current is referred to as Direct Current (DC) since it is of fixed electric potential. Figure 1 shows a plot illustrating the voltage over time as a comparison of alternating current and direct current.

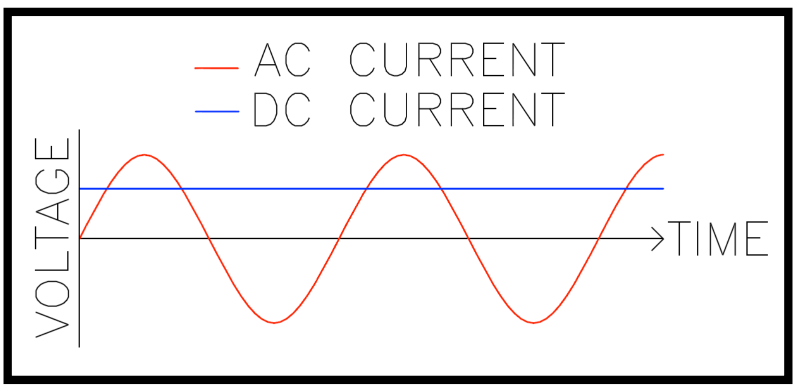

Figure 1: AC vs. DC Voltage Over Time

A reliable electric source was a major step forward in electrifying the world; however limitations exist when batteries are the only form of power. These batteries were one time use instruments that, through a chemical reaction, create electric potential, but these batteries had no way of being recharged after their use. Imagine in today's world if all of our electrical power were required to come from these one-time use sources, there likely would still be limited power and it would come at a high cost due to having to mine and process the elements that are used to create an electric potential. Volta's batteries, despite their limitations, remained the only reliable source of electricity for over thirty years until Michael Faraday introduced his dynamo in 1831 (Baigrie, 2007).

Dynamos

Dynamos are essentially generators that produce an alternating current as they convert mechanical energy into electrical energy. AC power might seem like a good thing in current society however there were virtually no processes in the 1830's that used alternating current. Almost all processes that started to use electricity were developed to use the DC produced in batteries. In 1832 Hippolyte Pixxi constructed a dynamo that used a commutator which periodically reverses the direction of the current in order to ensure a unidirectional (direct) current to the external circuit.

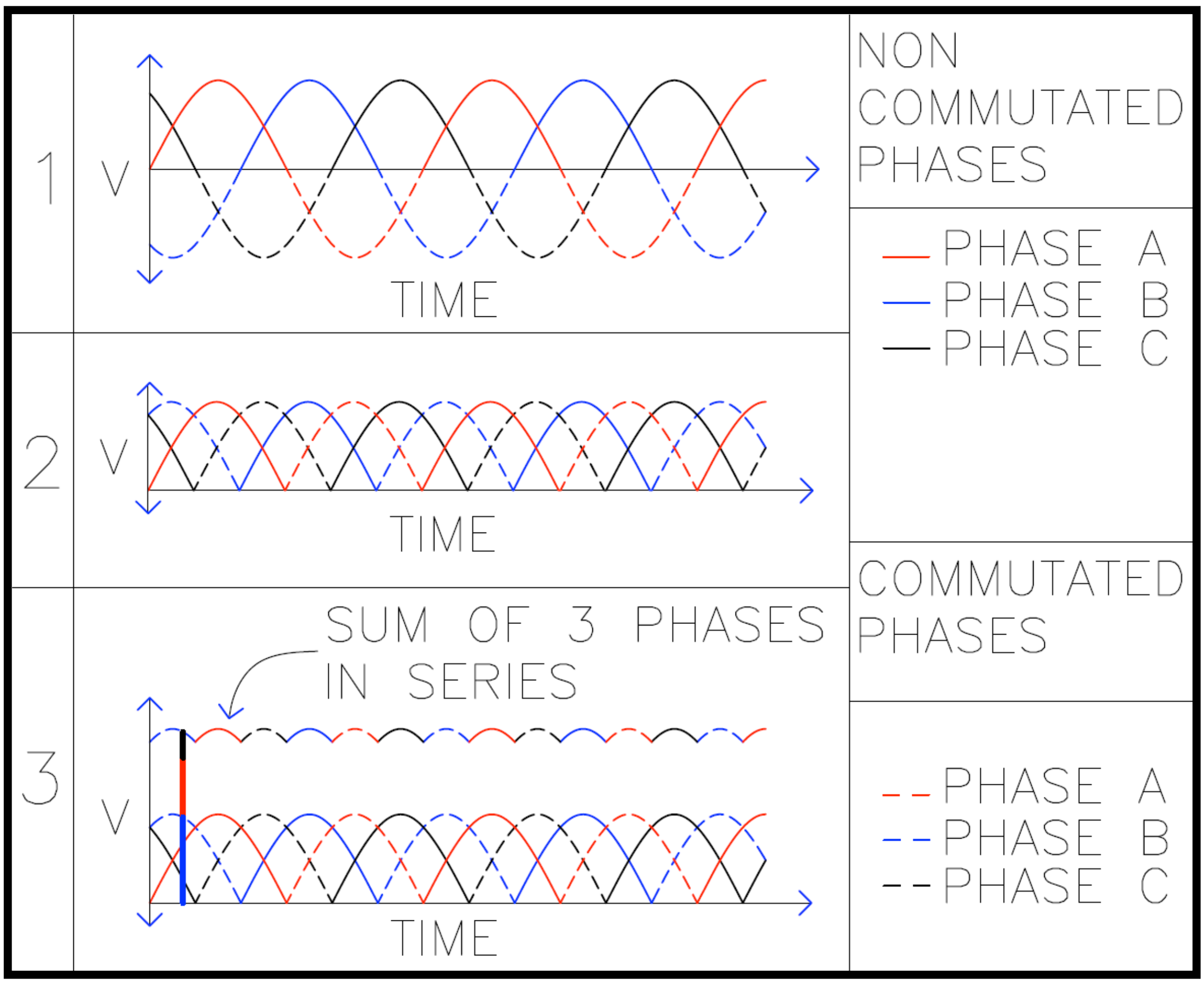

Figure 2: Commutation Graph

In Figure 2, Graph 1 represents a standard three phase current generated by a dynamo if it had three sets of pickups. Graph 1 represents the voltage that follows a traditional sine wave. Each of the currents is out of phase by 120 degrees of separation.

The first step, to obtain DC power from this configuration is through the use of a commutator. Graph 2, in Figure 2, shows that by reversing the direction of the current flow every 180 degrees, for each phase of power, the result is a wave that is the absolute value of the sine function over time.

The next step is to place all three commutated phases in series, represented by Graph 3, in Figure 2. When the three phases are in series, the voltage becomes the sum of the phase voltages, which is represented by the sinusoidal peaks shown in Graph 3 of Figure 2. The line towards the left edge of the Graph 3 shows the potentials of each phase stacked on top of each other at that particular instant in time. When done over every point in time, the voltage resembles the top line of the Graph 3. The voltage that is produced through commutation is not truly direct current since it varies slightly over time. Generation of this nature can get much closer to a DC current however, by adding more phases to the alternator thereby causing the voltage peaks to decrease until the voltage is within operating tolerances. Figure 3 shows a basic two pole split ring commutator. As current is induced along the coil of a dynamo, the split ring spins and, at the point in which the current would go negative, the brushes contact the commutator in the opposite position forcing it back into the positive region. Commutated DC power was an incredible advancement in electrifying the world. For the first time, the world had a device that was capable of turning mechanical energy into usable electrical energy.

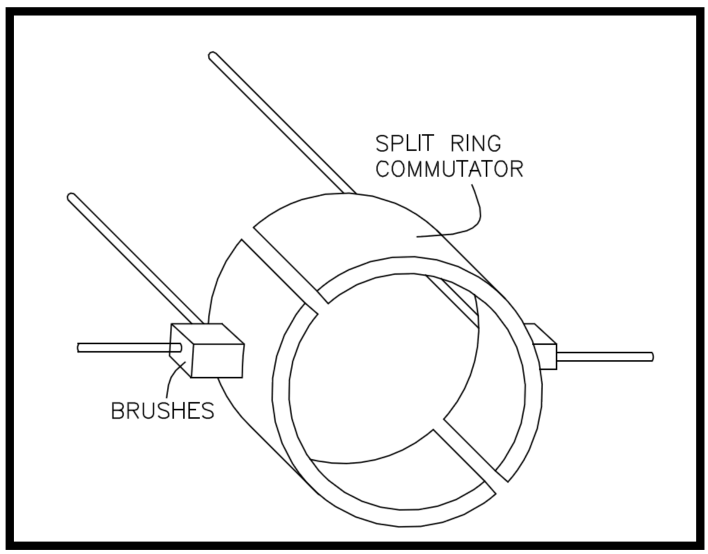

Figure 3: Split Ring Commutator

As the next few decades passed, these dynamos started to get more pickups and coils in order to produce higher current and voltage for producing electricity. In 1853 a Paris company, called Alliance Company, was founded to produce these machines with up to 96 coils and 48 magnets (Meyer , 1972). All dynamos being produced were commutated because the only uses for power at the time were for direct current; most commonly was electrolyzing water into hydrogen and oxygen. Keep in mind that this is over 50 years from when direct current had first been produced and there had been little advancement in the technology due to the lack of an electric motor that could convert this electric energy back into a usable mechanical energy.

Motors and Lamps

It was by accident in 1873 that a worker was carelessly hooking up a dynamo demonstration at an exposition in Vienna when he hooked two dynamos together and noticed that one of the dynamos he attached began to spin around at a considerable speed before disconnecting it. Within the next decade the development of the electric motor continued and was implemented into some of its first industrial uses (Meyer , 1972). At the same time this work had been occurring to produce electric motors in order to preform work, there was a similar effort to produce electric lighting.

The first electric lighting, an electric arch lamp, was introduced at the Royal Institution in London in 1809. Electric lighting however was very expensive because, for the first 40 years of this technology, batteries were the only widely available source of power and they were costly. Once the dynamo was introduced, interest in electric lighting increased almost immediately.

The first practical arc lighting installation using a magnetogenerator (dynamo with fixed magnets) occured at South Forland Lighthouse in England in 1858. By the mid-1870s arc lamps and generation machines were being produced in substantial numbers (Meyer , 1972). The majority of arc lamp installations remained in lighthouses until 1876 when Jablochkov (spelled Jablochkoff depending on source) introduced a simple, practical arc lamp shown in Figure 4 that consisted of two carbon rods placed 1/8th of an inch apart with a plaster binder between them to hold them into place. This was not only the first long lasting and practical arc lamp, but it had one key

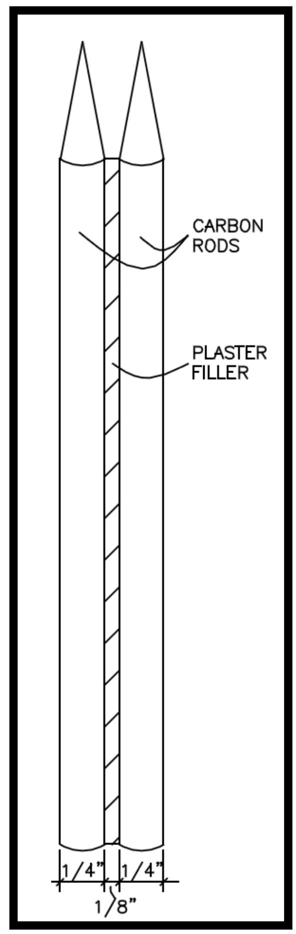

Figure 4: Jablochkov Candle

difference from all its predecessors, it was powered by alternating current. This allowed the rods to burn evenly rather than one to degrade much faster than the other resulting in up to a 16 hour burn time.

This lamp was the first commercial use for alternating current, however the industry had been growing around DC for more than 75 years before AC had its first commercial application. Several things had occurred during this time frame such as the introduction of the telegraph and other devices that ran exclusively on DC power. The next push in the lighting race was to produce lamps that were more efficient and longer lasting while being able to make a softer glow suitable for uses inside homes rather than only street lighting.

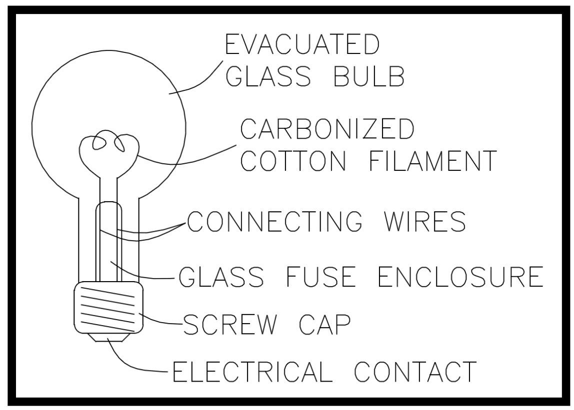

Figure 3: Components of Edison's Early Light Bulb

In 1878, Thomas Edison began to experiment with various filament materials in order to produce a longer burning incandescent lamp, which he believed was the key to cheaper, longer lasting lamps. Edison ran a successful press campaign in order to raise capital to finance his research. "A consortium of Wall Street financiers, including W.H. Vanderbilt (then the country's richest man), J.P. Morgan, and the directors of Western Union (Edison's one-time employer) put up a total of $300,000 to create a new company, the Edison Electric Light Company" (McNichol, 2006). While attempting to create an incandescent lamp, Edison was also working on improving the efficiency of the dynamo, which he successfully did by a substantial margin (90% efficiency compared to 40%). These new dynamos operated at a constant voltage of 110V. This is more or less the same voltage that is used today across several countries including the United States. On October 21, 1879 Edison created the first carbonized thread filament lamp that burned for 45 hours straight before failing. He applied for the patent on November 4, 1879 and was granted the patent on January 27, 1880 (Meyer , 1972).

The first centralized DC generation station allowing multiple customers to connect went online at 257 Pearl Street, Manhattan NY, on September 4, 1882. By the mid-1880s the public and designers were aware of alternating current due to its use in arc lamps throughout the city, however for use in houses, most knew it could be used with the new Edison light bulb. Alternating current had the large advantage that voltage could be stepped up and down to facilitate long distance transmission where DC power was limited to the produced voltage and a range of around ½ mile. However in the 1880s there was no practical alternating current motor in existence, of which there was high demand for the industrial sector.

Rise of Alternating Current

The alternating current industry continued to grow because of electric lighting despite the lack of a substantial financial backer until George Westinghouse purchased Gaulard and Gibbs in 1885. As demand for electric light grew from the industrial districts into the suburbs, more people were starting to use alternating current due to its ability to travel longer distances**.** The Edison Company heavily opposed the use of AC power saying it was dangerous due to the higher voltages that were being used to achieve these longer distances (which is probably true at the time). At this point in time most of the systems were approximately 133 Hz for residential applications and 25 Hz for industrial applications. The direct current motor was well established at this point still leaving a large gap for AC to fill in industry.

Nikola Tesla first introduced the alternating current induction motor in May 1888. Upon hearing this, George Westinghouse realized the value of this new motor and not only acquired the rights to the motor, but also acquired the services of Nikola Tesla. Electric services at this time were single phase, 133 Hz power which was not practical for use with electric motors due to the high rate of speed in which they would turn. Even with this in mind Westinghouse was willing to replace existing 133 Hz infrastructure that was only around three years old with 60 Hz three phase services that continue to be the standard today.

The next major blow to DC power was the installation of alternating current generators at Niagara Falls. Initially the plan was to use the hydroelectric power to compress air which would be supplied through piping to stations closer to the user to spin DC generators, thus solving the distance problem. Westinghouse eventually won the contract to install his generators and eliminate the need for this plan and creating the largest generation station of the time (Meyer , 1972).

War of Currents

What comes next is a battle between Westinghouse and Tesla vs. Edison and J.P. Morgan that is referred to as the "War of Currents", which turned into a series of scare tactics by Edison to try and show how dangerous these higher voltage alternating currents were. Both sides realized how much the future electrification of the world would be worth financially and would do almost anything to win the market. Edison and his associates, namely Harold Brown, set out to show firsthand how lethal AC was.

In one of Brown's first exhibitions he chained down a dog in front of a crowd and proceeded to electrocute it. He first started by electrocuting it several times by increasing the voltage of direct current up to 1000 VDC. He then switched over to AC and killed the dog with a mere 300VAC, however many of the spectators argued that the dog was on the brink of death already from the repeated shocks from the DC (Jonnes, 2003). Through the next few years Brown continued to grow in fame and was hired by the state as an expert on electrical execution. The state of New York had sentenced a man by the name of Kemmler to death by electrocution for the brutal axe murder of his wife. Brown had claimed that it would be quick and humane, however when the electrocution began it lasted for 17 seconds until the executioner turned the current off and the doctors came to examine the man. To their horror they found he was still alive and immediately ordered the power to be turned back on. When it had been completed the doctors determined he had been cooked alive rather than swiftly executed. This proved to be a blow for DC and Edison on the grounds that the AC was no longer thought to be an instant killer (Jonnes, 2003).

With this botched execution in the press the states were no longer ready to outlaw AC as Edison had been wanting all along. AC continued to grow and when Westinghouse received the contract to light the 1893 World's Fair in Chicago, which finally showed AC as a safe source to the masses, the growth of AC power exploded. Coupling this with the before mentioned generation at Niagara Falls, AC was in and DC was out. Westinghouse and Tesla refuted the scare tactics of Edison over the course of the next several years and with the further expansion of the grid over greater and greater distances the gap widened. What it finally boiled down to was the ability of AC to change voltage, be transmitted over long distance, and stepped down again for use. Westinghouse and Tesla eventually won the "War of Currents" and their standards are still used today. Edison may have won however if he had the DC-to-DC converter used today for changing voltages of DC power in order to facilitate long distance transmission.

AC and DC in Today's Society

Alternating current has become the standard for distribution in today's society due to the ability for the voltage to be stepped up and down during the War of Currents. This has changed very little over the past 100+ years even with the change in load profile. Alternating current is still how most devices are set up to receive power and is what is found in wall outlets around the world.

The United States power grid uses both AC and DC power for distribution. Alternating current is still the standard for distribution in most regions in the US due to its ease of integration with the existing system however there are exceptions that are starting to show up. High Voltage Direct Current (HVDC) is becoming more prevalent in today's society with the ability to change voltages in DC that did not exist until the middle of the 1960's (Okba, Saied, Mostafa, Moneim, 2013). DC distribution is becoming the standard for underwater distribution with things such as off shore wind farms due to the fact that when you run alternating current underwater it builds up a high capacitance. There are now many underwater DC power lines around Europe that connect various countries (McNichol, 2006).

Direct current is also used to tie together the various grid regions in the US. This has to do with the fact that, for a grid to function, all of the generators need to sync up their frequency so that the peaks of the sine waves all hit at the same point. When you are trying to tie several regions together this becomes very difficult. To get around this the grid uses DC power at these tie locations by converting from AC to DC then back to AC.

While alternating current is ever present in distribution more and more of it is being converted to DC at the user level. With the rise of the technology age we are using more DC every day. Most electronic devices use DC power for several reasons. Microprocessors that use direct current power to operate and send signals are a big reason for this shift due to the fact that a practical AC microprocessor has not been made yet. While plugging various electronic devices into the wall, most of these devices have a power source that converts this 120V, 60 Hz current into a usable direct current (typically 12V or less). For the majority of cases if it has a battery, it is actually a DC device that converts the AC power for storage.

Lighting is often thought of as an alternating current load, however in today's world more and more is actually DC. As the drive to increase efficiency moves forward we are turning to lighting sources such as fluorescent and LED (solid state) lighting to allow for this. These devices convert the AC power to DC through the use of a ballast (fluorescent) or a driver (LED), therefore they should really be considered a DC device.

Alternating current has a large hold on the motor market due to the fact that it has become the standard for over 100 years and AC motors are more readily produced as compared to direct current motors, which have actually been around longer. This is not to say that DC motors do not exist, in fact they are pretty common in certain applications, such as anything with a battery. A large number of DC motors exist in manufacturing processes that require large, speed controlled, motors due to the lack of a sizable Variable Frequency Drive (VFD). DC loads continue to grow due to the prevalence of the microprocessor and, at the present, we are happy to convert our AC power to DC in order to power these devices that play an expanding role in day to day operations.

Chapter 3 - Introduction to DC Microgrids

A microgrid is a localized grouping of generation, storage, and loads coupled to the centralized grid at one point. "The DOE (Department of Energy) and CEC (California Energy Commission) jointly commissioned a report from Navigant Consulting in 2005 that wrestled with this definition. The final report identified two 'Points of Universal Agreement' of what constitutes a microgrid, which remain valid today:

- A microgrid consists of interconnected distributed energy resources capable of providing sufficient and continuous energy to a significant portion of internal load demand.
- A microgrid possesses independent controls, and intentional islanding takes place with minimal service interruption (seamless transition from grid-parallels to islanded operation)" (Savage, Nordhaus & Jamieson, 2007).

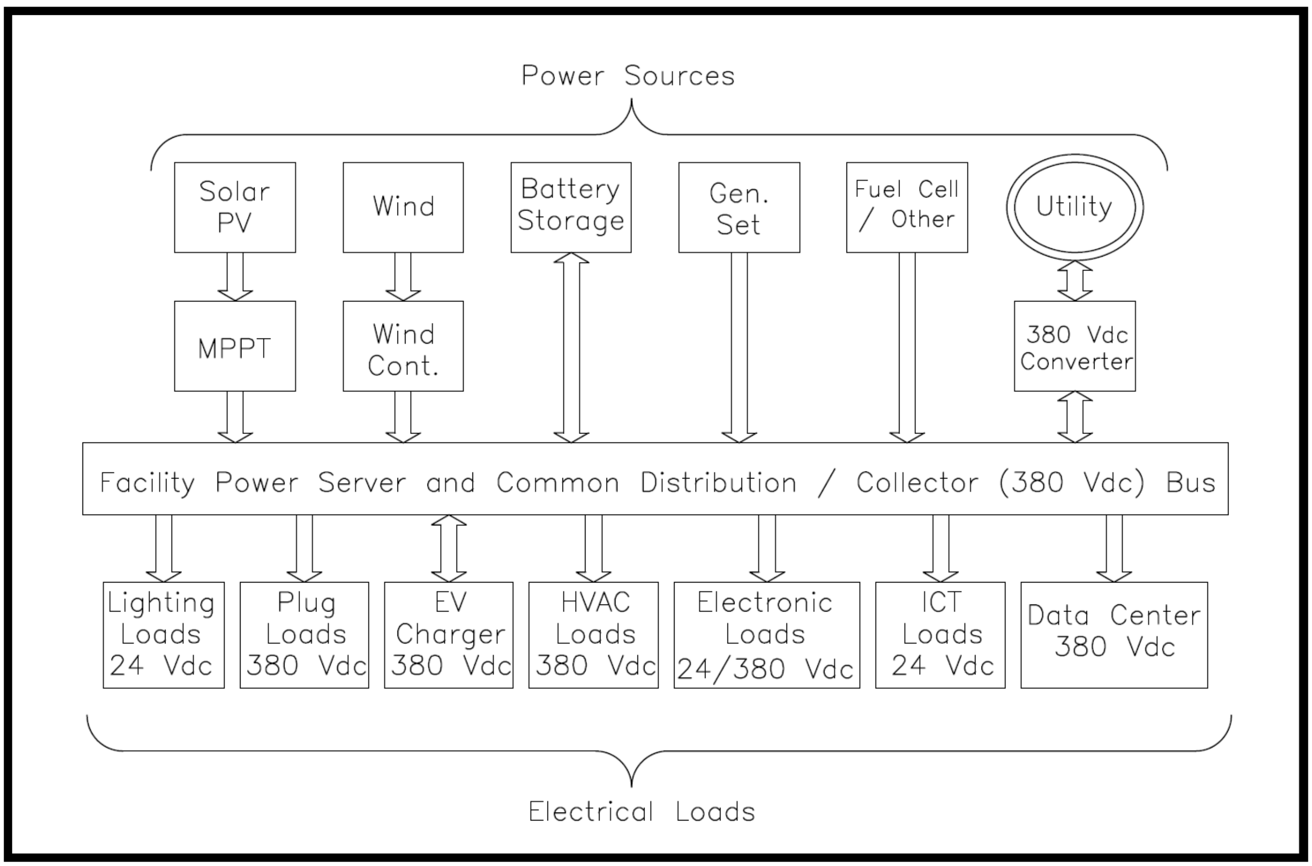

Figure 4: DC Microgrid Structure

For the purpose of this paper the microgrids are assumed to be operating on direct current power rather than alternating current for distribution. This does not mean that some components will not be alternating current, both AC and DC components will be considered within the scope of the paper. A standard DC microgrid configuration is pictured in Figure 4.

Power Distribution

A DC Microgrid distributes DC power throughout a building or campus for use in the building's loads. As demonstrated in Figure 4, the voltage for distribution in a building is often 380 VDC (voltage direct current). This is compared to either 120/208 3ϕ, 4wire, VAC (voltage alternating current) or 277/480 3ϕ, 4wire, VAC for most applications in the United States. Another key difference is the lack of phases in DC power. Most AC systems are three phase systems, but only one phase is present in a DC system. This 380VDC is used in several of the building's larger loads, such as HVAC and other large motor loads, in order to keep the current draw low. For small loads, such as lighting, the voltage is reduced to 24VDC for reasons that are addressed later in this paper.

Power Generation

Generation on these systems can be either AC or DC; however the AC sources will be converted to DC for distribution in many cases. It should be noted that in most cases two distribution systems are often used in buildings. AC distribution is still relevant in buildings due to the need for plug loads. There is not a wide spread standard for DC plugs and many products are not manufactured that use these DC plugs as a standard power source. DC microgrids use a single point of contact with the outside utility grid. It is a common misconception that these are stand-alone grids with no utility interconnection. While some of them are, it is not a requirement. Many microgrids use energy from the utility when they are consuming more energy than they are producing.

On-site generation is not required to distribute DC power but, there are advantages to having onsite generation that will be discussed in the next section. The sources will be referred to as microsources and for most applications will be limited to less than 1 MW, although in certain cases can range upwards of 10MW (Jiayi, Chuanwen & Rong, 2007). In most applications there is an AC to DC rectifier that will convert the grid AC power to DC to be pushed though the DC microgrid in a situation where there is not enough DC generation to cover the entire load. The various DC sources are combined in a DC Electronic Control Center (DC ECC). This then distributes the power to the various loads throughout the building. This is done in a similar manner to that of its AC counterpart with feeders, breakers, and control panels; however with the small DC loads it is common to use a Power Server Module (PSM) in order to manage these loads. These PSM's take in 380VDC and output 24VDC from several ports. These ports are often limited to 100W, limiting the sum of that circuit to the maximum limit of the particular port. However the PSM can be programed to have several ports operate off the same control signal allowing for an increase of power provided from a single control signal. These components make up the majority of a DC microgrid and are discussed in detail in following sections.

DC microgrids vary from traditional centralized generation of AC power and HVAC transmission and distribution in that all facets of these systems including generation, distribution, and storage are not owned by the utility company, but rather have a private ownership.

Chapter 4 - Advantages of DC Microgrids

The advantages of a microgrid can be classified into three primary categories:

1) System Efficiency
2) Reliability of Power
3) Safety

System Efficiency

Electrical efficiency has traditionally been defined as how efficiently the power within the building is being used. As a society, this creates a skewed result when measuring how efficient electrical systems are. For many purposes this is still an accurate measure when comparing AC buildings vs. other AC buildings. However, this type of comparison does not take into account the transmission and conversion losses that occur in the system, the losses are simply held constant between structures. This paper will only be interested in the losses occurring from onsite generation and the assumption is that all transmission remains in 60Hz AC form.

Conversion Losses

As discussed previously, the load profile has shifted from AC to more and more DC loads over the past several decades and is continuing down that path. The driving factor in efficiency for many of today's devices is the conversion from AC power to DC power. It is not possible to get a 100% efficient conversion from one form to the other. The energy is lost to either heat, magnetism, or shunted to ground depending on the conversion technique. As loads go more and more to DC the amount of these losses is increasing at the same rate. These conversions are happening all over buildings and they are often not considered when designing a system. By the same standard, many of these losses are amplified in conditioned spaces. For instance, when trying to cool a building to a desired temperature point, every British thermal unit (BTU) of energy that is introduced into the space must then be conditioned in order to satisfy the HVAC demand and keep the space comfortable. The refrigeration process requires electric energy in order to move heating and cooling from location to location; therefore not only is the owner of the building paying for the wasted energy that is lost in these conversions, but is then paying for the energy in order to run the air conditioner to remove heat from the space, further decreasing the efficiency of the system as a whole. This might seem like a good thing in the winter, when the building needs the additional heat. However, this heat is not usually in the needed location; these losses are often taking place in spaces such as above ceilings and in walls where they serve no use in conditioning the space for occupant comfort.

A study at Virginia Tech's Center for Power Electronics Systems found that more than 80% of all electricity used in an office building passes through a power electronic device that undergoes one or more conversions (Patterson, 2012). These losses however are not additive, but multiplicative. For an uninterruptable power supply (UPS), power is converted from AC power to DC for storage in a battery, then converted back into AC for the server plug. The server then converts it back into DC power for use in the processors. At this point there is an AC to DC to AC to DC conversion. Now, for arguments sake, say that this power is produced from a solar panel that the owners have decided to install on the roof. Photovoltaic panels naturally produce DC power that is then typically inverted. To get power from the solar panel into the server there is a DC to AC to DC to AC to DC conversion in a standard grid arrangement. Each of these conversions has losses between 10% and 25%. The Lawrence Berkeley National Laboratory (LBNL) estimates an average conversion efficiency of only 68% (Patterson, 2012). Assuming only a 10% loss at each of these conversions is a generous number when using high quality electronics.

For example, look at what happens when trying to supply 500W to a server module. If there are four conversions the natural instinct would be to simply use the following equation: 500*10%=50W per conversion times four conversions results in a total loss of 200W which would mean the generation draw would be 700W (500W for the load and 200W in loss). However, with losses being multiplicative, what actually happens is:

$$\frac{500W}{90\%^4} = 762W$$

This might not seem like a huge difference, 62W is not that much power. However, if assuming a $0.10 kWh rate for electricity and that this is a year round load, which many servers are, the equation looks like:

$$62W * \frac{24H}{Day} * \frac{365Days}{Year} * \frac{1kW}{1000W} * \frac{\$0.10}{kWh} = \$54.31\ Dollars/Year$$

Total losses from the system are 262W not just the 62W difference yielding:

$$262W * \frac{24H}{Day} * \frac{365Days}{Year} * \frac{1kW}{1000W} * \frac{\$0.10}{kWh} = \$229.51\ Dollars/Year$$

$229.51 per year for a single server running around the clock in wasted energy is a sizeable amount. Keep in mind that these are very conservative estimates that do not include the HVAC energy expense to remove the wasted heat from the space.

What about losses from DC to DC converters? These converters are more efficient than AC to DC or DC to AC; often with efficiencies of 98% for most applications. Examining the same scenario but with DC distribution: Start with the PV panel producing power at a unknown voltage, this feeds into a DC to DC converter that brings the voltage up to 380VDC for distribution throughout the facility. This power is then run through a DC to DC converter that steps the voltage down to 24VDC. This 24VDC is then used to operate a charge controller in the UPS. A charge controller is nothing more than a DC to DC converter with some programing to shut off when the battery is charged, to protect the battery cells. From the UPS it is then stepped down inside the computer from 24VDC to a usable voltage of often 5V. So the scenario is a DC to DC to DC to DC to DC conversion chain. The conversion chains for this setup can be seen in Figure 5.

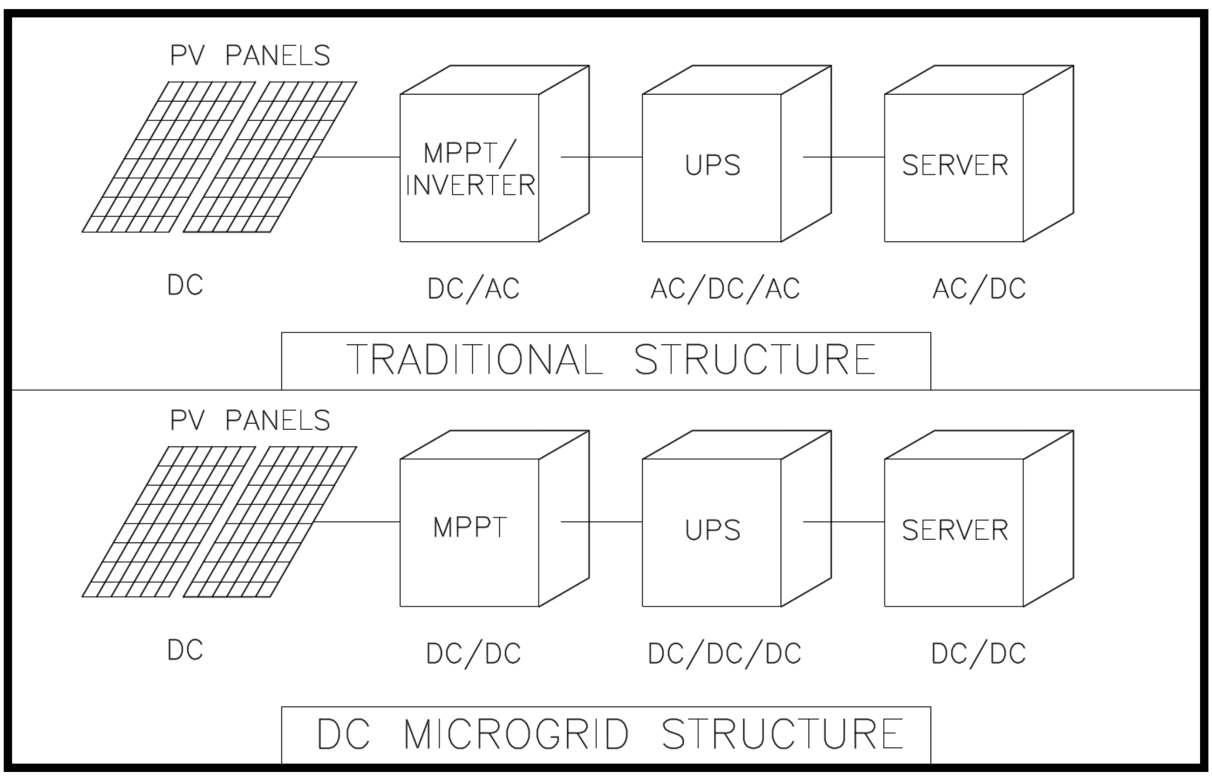

Figure 5: Conversion Chain Representation

The same numbers of conversions were used in this example to show an apples to apples comparison. In many cases there are far fewer conversions in a DC microgrid than there would be under normal distribution conditions. Even under this worst case scenario with the same 500W server load 24 hours a day, 365 days a year the equation is:

$$\frac{500W}{98\%^4} = 542W$$

The yearly cost of loss for this case is:

$$42W * \frac{24H}{Day} * \frac{365Days}{Year} * \frac{1kW}{1000W} * \frac{\$0.10}{kWh} = \$36.79\ Dollars/Year$$

By choosing to use this DC distribution system over an AC system the owner saves a total of:

$$\$229.51 - \$36.79 = \$192.72/year$$

These numbers are very high due to the number of conversions. What happens if the UPS is removed from the equation? The number of conversions reduces by two and equation looks like 21W of wasted energy for the DC to DC conversions at 98% efficiency compared with 117W of inefficiency for the 90% conversion efficiency in the AC to DC conversion, as shown below:

$$\frac{500W}{98\%^2} = 521W \quad \frac{500W}{90\%^2} = 617W$$

A savings of 96W which equates to:

$$96W * \frac{24H}{Day} * \frac{365Days}{Year} * \frac{1kW}{1000W} * \frac{\$0.10}{kWh} = \$84.10\ Dollars/Year$$

With more power conversions the losses become exponentially higher even without including the additional strain on the HVAC. The additional cost on the HVAC has too many variables to estimate, so in all fairness these calculations will be left out of the report, although they are certainly not insignificant.

It is extremely hard to name a load in most buildings that would truly require an alternating current source. The next section explores some of the larger loads and possible sources of distributed generation.

System Loads: Lighting

The vast majority of lighting that is being produced in the United States is either fluorescent lighting or solid state (LED) lighting. These devices must rectify the distributed AC to DC, and then undergo a DC to DC conversion, in the case of solid state lighting, to produce a suitable voltage for the lamp. In the case of fluorescent lighting it undergoes conversion to DC then back to AC at a frequency of 20,000+ Hz. Thomas Edison invented the incandescent lamp to run on direct current power and Tesla merely noted that it could just as efficiently run on either form of current. Apart from a few sources of High Intensity Discharge (HID) lamps, lighting loads would actually prefer DC power to the AC that has traditionally been feeding them.

How Electronic Ballasts Work

Many electronic ballasts work by using a bridge style rectifier with a capacitor across the diodes to produce a basic DC current. This DC signal is then converted back into a high frequency AC signal with a positive only square wave signal. Figure 6 represents a basic electronic ballast architecture.

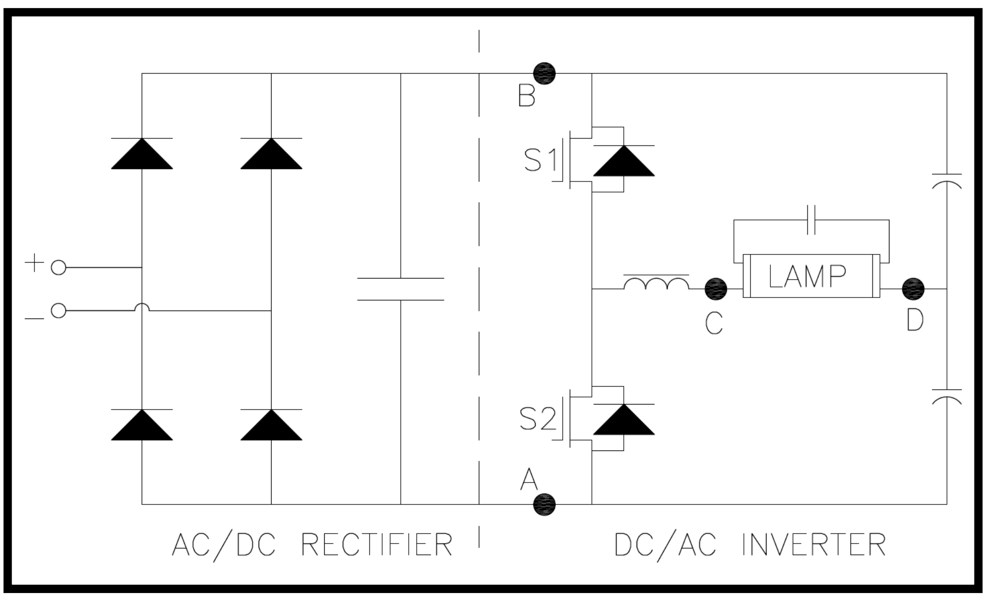

Figure 6: Ballast Architecture

If the input nodes on the left edge are supplied with an alternating current, the diode set-up shown will only allow the voltage across A and B to remain in the positive voltages, creating what is basically the absolute value of the voltage sine wave. Current through a diode can only flow in one direction and with the bridge diode set up the current will be forced through the other two diodes resulting in the reversal in current for that half of the current cycle. The solid line in graph 1 on Figure 7 indicates the resulting voltage. When these diodes are forced to try and take current in the wrong direction they become an open circuit. To get the diodes to act in this manner they initially take some of the power and heat up, becoming open. This power draw of the diodes is a component associated with the loss in a rectifier.

The other component that is required for a DC output is the capacitor across the bridge rectifiers. This capacitor is installed to regulate the voltage over the peaks and valleys of the sine function as it charges and discharges. The output from the capacitor can be seen in graph 2 in Figure 7 and is represented by the blue line. When accounting for both voltages, in parallel, the combined voltage seen across A to B is represented by graph 3 in Figure 7. Although the voltage is not completely constant, the drift in voltage is relatively small and is within most components operating tolerances. This charging and discharging of the capacitor also leads to losses in a rectifier.

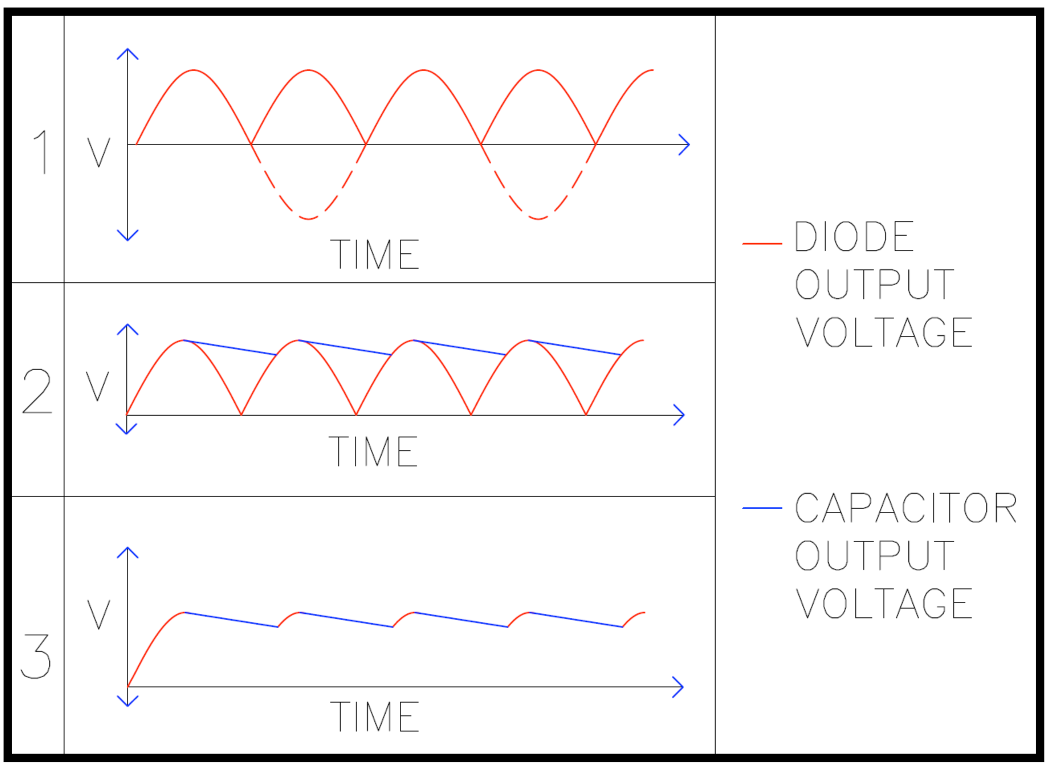

Figure 7: Rectifier Output Plot

This is how most rectification is done in electronic components, however for fluorescent lighting this DC voltage is then inverted back at high frequency. S1 and S2 in Figure 6 represent metal-oxide-semiconductor field-effect transistor (MOSFET) switches that are set to open and close opposite of each other with a time delay in between so that for a brief period of time both switches are open. This delay is done to insure that there is not a short circuit that takes place. The resultant voltage across the lamp is a square wave with the peak that has a value of the DC voltage from the rectifier section. There are losses associated with opening and closing the MOSFET's and also through the change in current in the inductor.

For solid state lighting, simply remove the inverter from this configuration and the lamp would be placed across the points A and B. Removing the MOSFET's simplifies the equation, eliminating points of loss and leading to a higher efficiency.

System Loads: Motors

Most of today's motors are a variation on Tesla's induction coil motor, however these often have poorer efficiency than their DC counterparts. It is for this reason that many industrial applications have long been using DC motors in manufacturing processes. In addition to their inherent efficiency, it is easier to implement speed control on a DC motor. This is done by simply changing the resistance in the circuit, much like using a dimmer switch on the wall for an incandescent lamp.

Why can't this be done with AC induction motors? When using a variable resistance for control, voltage potential across the load is directly affected. This works just fine in DC because the voltage potential is translated directly into current driving the motor. However in an induction motor the voltage and current are both required to remain near their design conditions. The speed of the motor is directly dependent on the magnetic flux that is generated in the windings. Therefore, in order to change the speed of an AC induction motor it is actually the frequency of the current that needs to change in order to vary the magnetic flux. The frequency modulation of the power is done with what is referred to as a Variable Frequency Drive (VFD). These VFD drives operate by taking the 60Hz AC power that is delivered, then converting it to DC, then converting it back to AC power with a variable frequency in order to control motor speed. AC induction motor control requires an AC to DC to AC conversion for their normal operation, creating losses.

VFD's have been extremely expensive due to the power electronics that are required for this to occur, meaning that the operation of a conventional induction AC motor has largely been either on or off. Why is this bad? Think about this as if driving a car. Would it be logical to floor the gas pedal all the way, get up to full speed, and then slam on the breaks, repeating this process over and over to reach the goal? This is exactly the operation for many motors in the current market.

Take for example an air conditioner at a home. When the house needs cooling, the air conditioner kicks on to full blast, runs for a short period of time, then kicks off again, only to repeat the cycle a few minutes later when the thermostat tells the air conditioner to cycle again. Several air conditioner manufacturers have been rethinking this strategy and putting in variable speed compressors to stop this from occurring, often providing energy savings of upwards of 30%. These systems are becoming increasingly more popular with the demands to reduce building energy usage. DC microgrids are eliminating a conversion of power, saving around 10% in losses. DC microgrids and motors offer the opportunity to make speed control cheap enough to be used in a greater variety of applications that would be too cost prohibitive given today's VFD pricing.

System Loads: Heating

Heating equipment is extremely dependent on the location of the building and availability of utilities. Although natural gas or propane furnaces are more expensive to purchase and install than their electric counterparts, the fuel can be significantly cheaper than electricity depending on location. For locations that require a lower heating load it is common to use either electric resistance heating or a heat pump due to the gas equipment being more expensive. For gas furnaces the only load intensive electric component is the fan that circulates air over the coils and around the home. Fans are common in all types of heating systems and are nothing more than a motor load, which could benefit from cheaper speed control and higher efficiency to allow for reduction of short cycling. Electric resistance heating does not care if the current is AC or DC and again most of the time contains a fan.

The other major form of heating in the United States is the heat pump. A heat pump is very similar to an air conditioner, often using the same coils; it is a refrigeration cycle that operates in the opposite manner than normally thought of by removing energy (heat) out of cold (outdoor) air and moving it into the conditioned space. This has found to be more efficient than just using electric resistive heating, leading many owners to install heat pumps over electric resistive heating. Heat pumps suffer the same drawbacks as air conditioners by turning on full power just to kick off and repeat the cycle. By incorporating speed control and increased efficiency in the compressor short cycling could be prevented and efficiencies could substantially increase.

System Loads: Plug Loads

Electronic devices are one of the largest sectors of plug loads in today's society and many are DC loads that are rectified down from AC. Below is a list of various plug loads and their potential savings on the national scale (Savage 57). These potential savings represent figures that assume DC generation and DC distribution removing in both a DC to AC and an AC to DC conversion.

Device	MWh Used	Potential DC Savings	MWh Savings
Refrigerators	160,158,600	40%	64,063,440
Indoor/Outdoor Lighting	103,113,000	15%	15,466,950
Microwave	19,801,800	25%	4,950,450
TV	33,960,600	15%	5,094,090
DVD Player	11,593,800	15%	1,739,070
Cable Boxes	2,975,400	15%	446,310
Desktop Computers	17,647,200	15%	2,647,080
Laptop Computers	1,333,800	15%	200,070
Printers	4,617,000	15%	692,550
Stereo Systems	5,130,000	15%	769,500
Phone Charging	4,514,400	15%	677,160
Recharable Tools	2,154,600	15%	323,190

Table 1: Residential Plug Loads

Table 1 represents several large plug loads throughout the United States. The plug loads continue to grow in the US every year, particularly in the residential sector, providing additional advantages for DC microgrids over the conventional AC distribution system.

Generation

With the changing in load profiles to increased DC power, the benefits of new, localized distribution systems are more relevant. Renewable energy sources such as photovoltaic (PV) and wind power have been growing steadily in popularity due to both the socio-economic climate and the increasing affordability of each. In addition to the renewables, many owners are opting to have other sources of onsite power such as a fuel cell or micro-turbines for use in cogeneration applications. "The US Department of Energy estimates that the energy market penetration of distributed generation could be as high as 30% by 2030" (Cetin, Yilanci, Ozturk, Colak, Kasikci & Iplikci, 2009).

Photovoltaic Panels

PV is naturally a DC source, however it is time variant depending on sunlight conditions and other factors such as temperature and atmospheric conditions. Many of these systems today use what is referred to as a Maximum Power Point Tracker (MPPT) in order to maximize the amount of power that can be produced from an array. These MPPT's are essentially nothing more than a DC to DC converter with some clever programming that forces the input voltage to be at a certain point on an array's I-V curve. For most systems however, the DC that comes out of the MPPT is then inverted to get 60Hz AC power at a usable voltage to feed into the distribution system. The system could gain upwards of 10% efficiency by simply removing the inverter and using the power in its native DC form

Wind

The type of wind generation that would be used in small distributed systems would not be the large synchronous generators that naturally produce 60Hz AC power. Small wind turbines are often permanent magnet generators that produce power in alternating current form, however the frequency and voltage depend on the rate of rotation of the turbine. The output voltages on small turbines can range from a few volts at low speed to upwards of 600V at full generation. The frequency is also directly proportional to the rate of the spin and the number of poles on the generator; however, small, permanent magnet generators often only produce power in the 20Hz range. Due to this occurrence the AC power that is produced is rectified to DC power, then inverted to get back to 60Hz. For use in DC microgrids these small wind generators would simply require replacing the inverter with a much more efficient DC to DC converter in order to get a usable output DC voltage.

Fuel Cells

Fuel Cells, regardless of the specific chemistry of the cell, all naturally output DC power. These devices simply harness the energy from chemical reactions to produce an electric potential that is not time variant. The voltage output from a cell is typically less than 0.7 Volts. These cells are placed in series to produce a higher voltage to feed into an inverter. In most applications fuel cells use a DC to DC converter to increase the voltage further before inverting the power to produce 60Hz. Fuel cells can easily be incorporated into the DC microgrid by removing the inverter and specifying the DC output at 380VDC.

Microturbines

Microturbines have the same problem as the small wind generators. They produce AC power but it is at an unusable frequency, in this case often in the several hundred Hertz range. This then goes through a standard double conversion to get a usable frequency and voltage out of the source, incurring significant losses in the conversion process.

Additional Efficiency Concerns

Efficiency Measurement

Onsite generation sources are becoming popular in new construction due to their ability to increase overall building energy efficiency and to reduce owner utility costs. Although they might not be more efficient than purchasing electricity, as in the case of fuel cells and microturbines that burn fossil fuels to produce energy, they save the owner money over time in reduced energy bills, which is what most of the energy standards are based on. The current energy standards are typically based on reduction in operating cost as the baseline comparison leading to the increase in such technologies, due to the relative low price of natural gas in the current market.

Site vs. Source

Energy efficiency is thought of as either site or source efficiency. There are substantial losses incurred when moving energy across long distances, which is partially the reason why electricity is very expensive as an energy source when compared to the energy in natural gas. It is much more efficient to move natural gas to the location it is needed than it is to distribute the electricity over the same distance. This cheaper energy source is driving owners to begin to produce their own local sources of power if the capital investment is possible. This, paired with the added benefits of being able to capture the waste heat, from energy production, for other uses in the buildings, have dramatically increased the use of local generation systems in many sectors.

Grid Strain

Another inherent advantage of having local power sources is the reduction of strain on the existing infrastructure in the United States. The infrastructure in many parts of the US has been stretched so thin that many power companies are incentivizing owners to have their own power source. They do this by keeping these generation sources (often their emergency power sources) on call; when the power company calls, the owner turns on their generation and drops off the grid. This is often done when the power company is nearing peak capacity. This lower strain on the power grid causes lower currents to be drawn along transmission lines allowing them to operate more efficiently, saving energy for the system as a whole.

Overview

The efficiency of DC microgrids, especially when paired with onsite generation, can save over 20% of the energy used by the baseline according to Lawrence Berkeley National Labratory. For more examples and case studies concerning the efficiency of DC microgrids, please see the Current Applications section.

Reliability of Power

Reliability of Distribution

Reliability is a major concern for a large number of industries and businesses. Many of the power failures that occur do not happen as a result of issues with generation. Transmission has long been the weak spot for reliability. This is not hard to imagine when you consider the distances that much of the power is traveling. Often it is things such as ice storms or strong winds that can cause these circuits to be compromised. Other times it is things such as lightning strikes, car accidents, or something crossing the lines that can lead to a power outage. The obvious answer to solve these problems is to simply eliminate the transmission lines and produce power on site. Fewer lines equal fewer places for failure. Many DC microgrids have the ability to draw fully from the grid when the onsite generation sources are offline due to weather or maintenance. Gas services that feed devices such as the microturbines and fuel cells are significantly more reliable than electrical services due to the protected nature of the infrastructure. Overall, the nature of onsite generation paired with grid redundancy results in a more reliable system than a standard AC only distribution system in a building, as well as providing a higher quality power (Justo, Mwasilu, Lee & Jung, 2013).

Backup Power

Reliability, in many applications is not just a nice consideration but rather a requirement for design. In applications, where reliability is a primary concern, there are multiple redundant systems in order to insure that there is not an interruption of service. When backup power is a requirement, it often involves various backup power sources. These are often things such as uninterruptable power supplies (UPS's), stand-by generators, or in certain cases things like the fuel cells or micro turbines that were mentioned before, however fuel cells or micro turbines are not always classified as such. The fuel cells are often not considered a source of emergency power because the fuel source (natural gas) is not stored on site, therefore fails to meet the requirement. However, there are many times that the owners wish to have back up power that is not code driven in which fuel cells and microturbines work just fine, as we have already discussed the reliability of the gas supply. In a few cases it is possible to apply for a variance with the Authority Having Jurisdiction (AHJ) on the job and they can allow these sources to count for emergency power.

Standby generation is typically in the form of a diesel generator that naturally outputs 60Hz power. For these generators or other sources that naturally operate at 60Hz to be utilized in a DC microgrid, the power is simply rectified into DC power and fed into the DC microgrid. This may seem inefficient however as a general rule the larger the inverter the more efficient it is. Doing this at one location is more efficient than doing it hundreds of times all over the building. In addition to that, remember that this is only for emergency generation means. Short run times on these systems still mean that over the course of a year there are very few losses that occur.

UPS's

For critical loads that cannot shut down for even a brief period of time, the only option is a Uninterruptable Power Supply (UPS). There are two types of practical UPS's available: The most common type is nothing more than a rack of batteries that are being charged whenever there is normal power available. When the normal power fails, the batteries discharge, providing a continuous power source for the load. These devices, in a normal operation, take the AC power; convert it to DC to charge the batteries then convert it back to AC for use on the load, where it is commonly converted back to DC for use. The systems often operate at only around 80% efficiency when accounting for the conversion losses.

Flywheels are the second major category of UPS. Flywheels essentially use a motor to turn a flywheel with a large rotational inertia while normal power is operational. If power fails the flywheel continues to spin for a short period of time turning the motor into a generator and producing power. These often tend to use an AC to DC to AC conversion when they are discharging due to the speed of the flywheel slowing down as it reaches the end of the discharge and the need to maintain 60Hz. To make this DC ready, the last inversion process would be removed to increase the efficiency of the system.

Easy integration and energy savings for backup power is one of the large draws for utilizing a DC microgrid. It not only eliminates losses in conversion for normal operation it also allows for the backup power source to last for a longer time than its AC distribution counterpart. This often means being able to slightly downsize the UPS and saving upfront capital costs.

Safety

Safety has, and will always be, of top priority in electrical design. Often if there is a lack of knowledge about a subject, people tend to not know of the safety concerns regarding a new technology. DC microgrid systems have been in development and have been in use for several years. The National Electric Code (NEC) does not distinguish between AC and DC current for anything under 600V. Therefore it is possible to simply treat most of the wiring in the same manner that would have been required if designing an AC system. Although there are different technologies that are used for circuit and life safety protection there are many products that are currently listed by UL for use in these situations.

Conductor Sizing

Sizing conductors is often something that contractors worry about, but in this case it is based purely on current draw and the NEC does not specify current type. Actually, using the values listed in the table for use on AC will cause slightly oversized wire in a DC system. This has to do with the skin effects that occur in AC, which causes the current to flow mainly on the perimeter of the conductor, while the DC utilizes the entire conductor in the same way.

Conductors are required to be sized using NEC leading to a more efficient distribution due to a lower perceived current by the conductor. This leads to a little less loss of power through the same conductor assuming the same current through it.

Voltage

Most of the smaller loads in a space, where it is possible for occupants to come in contact with electricity, would be delivered as 24VDC. This voltage is significantly safer than a standard 120VAC system given the proper overcurrent devices. If the load on the DC circuit is under 100VA and the voltage is under 30V, it can be classified as Class 2 cabling in the NEC. This cabling is not required to be run in conduit, provided that the shielding on the cable meets the proper smoke rating for use in the location concerned. Cabling that does not require conduit allows for a lower cost of install.

Advantages Overview

Overall, DC microgrids save the owner substantial energy over the traditional AC distribution system. The more conversions in the system the more losses occur, and remember that these losses are not additive, but rather multiplicative. DC power works more efficiently with onsite generation sources than a traditional AC system. There is an increased reliability from having onsite power by eliminating possible points of failure in a large distribution system. They integrate easier and more efficiently with UPS systems and are often times safer than 120VAC at locations that occupants can come in contact with power.

Chapter 5 - Disadvantages

There are several current drawbacks to DC microgrids. Many of these drawbacks have the ability to be eliminated in the future with continued investments of both time and money, taking these systems up to wide spread use. The major drawbacks that will be addressed are:

1. Code Compliance
2. Efficiency Metrics
3. Unfamiliarity
4. Initial Cost
5. Lack of Incentives

Code Compliance

As discussed, the potential energy savings of DC microgrids are perhaps their largest advantage, however with today's energy standards the energy cost savings are tough to document. Here are some concerns when dealing with two of the most common energy measures in the United States: ASHRAE/IES Standard 90.1 & USGBC LEED

ASHRAE Standard 90.1 has become one of the most commonly adopted energy codes in the United States. The other common energy code is the International Energy Conservation Code (IECC), which is not only adopted in the United States but also around the world. The IECC however has a section that states if the building is ASHRAE Standard 90.1 Compliant then it is considered to be IECC compliant. This was done in order to accommodate the HVAC industry in the US that has become very accustomed to the use of Standard 90.1.

According to ASHRAE Standard 90.1-2010 the standard provides:

"Minimum energy-efficient requirements for the design, construction, and a plan for operation and maintenance of:

1. New buildings and their systems
2. New portions of buildings and their systems
3. New systems and equipment in existing buildings
4. New equipment or building systems specifically identified in the standard that are part of industrial or manufacturing processes. "

The standard then goes about setting the criteria for determining compliance with the requirements and lists the exemptions from the standards which includes:

1. Single family houses
2. Multi-family structures of three of fewer stories above grades
3. Manufactured houses
4. Houses that use neither electricity nor fossil fuels.

This standard has two options for proving energy efficiency compliance. The first option is to follow the prescriptive path of the standard. This allows the designer to prove that their building is compliant by showing that the pieces of the building that are specified in the standard meet or outperform the baseline value set for that particular piece of equipment. By following this path it states that if all of the parts are compliant, the building would therefore be compliant with the code as a whole.

The prescriptive method lists specific efficiencies for pieces of equipment that are traditionally AC equipment. For instance, with motors it does not specifically list DC motor efficiency. It states motor efficiencies for various types, however it does not state what DC motor efficiency would be required. DC motors are outside of the scope of the standard and therefore do not have a minimum requirement. The problem is that if the designer is trying to show a certain percentage savings over a baseline to document potential savings from a DC microgrid to an owner there is no standard baseline for DC motors to compare against.

DC microgrids are able to show compliance with the current standard, as it is currently written in the 2010 edition. Most designers and owners are not always looking to just be compliant with this or similar codes. Beating the baseline by a substantial margin has become big business in the US over the past few years. This not only substantially increases the value of the building, but reflects directly on the company. In addition to just being able to market their efficiency, energy modeling is used for trying to decide if the investment in a more expensive system is economically justifiable and meets the return on investment requirements for the owner.

The other option for compliance with ASHRAE Standard 90.1 is referred to the Energy Cost Budget Method. This method allows for the designer to combine all of the energy requirements into a single energy usage number and then prove that their building will beat that number through the use of a computer program based energy model. This allows the designer to have a compliant building even if one particular part of the system is not compliant within the standard. This gives the designer significantly more freedom than the prescriptive path while still achieving a set standard of energy efficiency. These baselines are created using energy modeling software that ASHRAE has found to be acceptable for determining the energy budget, and states what software and options must be available in the software in order to be compliant with their modeling parameters.

ASHRAE 90.1 sets out the method that must be used in order to create the baseline energy model. The designer's model must be compared against the baseline model, and have an energy usage less than the baseline for demonstrating compliance. This compliance however is only as accurate as the energy modeling software used. These software packages that have been developed have always been created to deal with AC power. With so few buildings using distributed DC power there have not been any companies that have invested the resources that would be required to develop the ability of modeling DC. One of the main reasons that this investment has not occurred is there are not enough buildings or systems that have been in place for a substantial period of time in order to verify a building model. This is a result of a very fast changing system with the advancement in renewables and the overall efficiency of DC components over the past years. There have been very few of these DC buildings that have been audited, meaning that limited amounts of data have been collected that would be relevant to developing a program for modeling DC power in buildings.

This lack of long-term information inhibits the designer's ability to use these systems in buildings that are required to show compliance with the standard. This is a major setback for anyone who wishes to implement a DC microgrid because they would have to develop other methods of compliance for the AHJ, driving up the time and cost of the project possibly hindering the project.

Efficiency Metrics

The software used for the Energy Cost Budget method of ASHRAE 90.1 is often used to show compliance with performance based certification systems such as United States Green Building Council's Leadership in Energy & Environmental Design (LEED). This performance rating system has quickly become one of the United States most well recognized indexes for determining the buildings' proposed environmental impact. The LEED standard has been broken into many separate sections that split the projects up by the building classification. This discussion will be referring to the LEED for New Construction and Major Renovations V2.2. The LEED rating system is a gauge for determining the impact of a building in several different categories. Points are earned for each item in a specific category and then totaled up to determine where the building falls on the ratings scale. There are 110 possible points in this particular version of LEED. The standard has four levels of achievement as follows:

Certified: 40-49 pts.

Silver: 50-59 pts.

Gold: 60-79 pts.

Platinum: 80+ pts.

In addition to the points that can be achieved there are also certain things that must be met before you can begin the attain points. These items are referred to as prerequisites and they are required for a building certification

This standard is impacted in several different ways by DC microgrids. This first is Energy and Atmosphere: Prerequisite 2. This requires that the building meets a minimum threshold for energy efficiency in order to be compliant. The system allows for two different compliance paths to show compliance for the prerequisite. The first is to use a whole building energy simulation to show compliance with ASHRAE Standard 90.1-2007 baseline model. As discussed in the last section this is very difficult to do because the software has not yet been developed to show compliance. The other option for compliance within this section is to follow the prescriptive path in one of three standards depending on building type. However, of these three standards, none of them have set forth sections dealing with DC power. Therefore it is extremely difficult to even get the prerequisite in order to be considered for rating. To get a building certified it would likely require that the designer demonstrate energy compliance with other means by working with the representative from USGBC certifying the building.

There are two large point value sections of the standard that allow for substantial point gains towards certification. These two sections are EA Credit 1: Optimize Energy Performance, and EA Credit 2: On-site renewable energy. Table 2 represents the number of points available in each category and the total possible percentage of points (out of 110) that can be obtained from each category.

Relevant LEED Point Potential and % of Total Points			
Credit Number	Credit Name	Credit Points	% of Total Possible Points
EA 1	Optimize Energy Performance	1-19	17.27%
EA 2	On Site Renewable Energy	1-7	6.36%

Table 2: LEED Points per Category

EA Credit 1 is worth up to 19 points and basically states that if the design can beat the ASHRAE Standard 90.1-2007 by a certain percentage, then the project gets a representative quantity of points. The more that can be saved off the baseline, the more points the project can receive. As previously stated, DC systems are difficult to model in regards to this standard and therefore it is difficult to show savings over a ratings system that was developed around AC power.

EA Credit 2 is very similar to EA Credit 1 in many ways. Credit 2 varies in points from 1 to 7 and is based on percentage of the energy produced on site from renewable sources. Also, like credit 1, the baseline is the ASHRAE Standard 90.1-2007 whole building energy simulation. This energy model however is not capable of demonstrating a lower energy usage that could occur from using DC architecture. If the model was capable of utilizing DC power then the total energy usage for the year would be less, therefore making the renewable energy a larger percentage of the yearly consumption resulting in being awarded more points from EA Credit 2.

The current standards and rating systems have not yet been developed to allow for the use of DC microgrids within their text. Not only can the prescriptive compliance be difficult, but also the energy modeling available is limited and difficult to prove accurate due to the relatively new nature of the technology. While rating buildings with DC microgrids is difficult and more expensive than a standard building, it is possible by working with the AHJ and the USGBC official.

Unfamiliarity

Unfamiliarity with DC microgrids is one of the biggest setbacks to overcome, as with any new system or technology. It takes time to develop these new technologies and get them implemented in enough cases that they become familiar to the public, contractors, owners and ratings agencies. One of the biggest places that this can become a problem with DC microgrid systems is on the contracting end.

The electrical contractors that are tasked with the installation of these products and systems are often required to troubleshoot problems with a new system. Therefore, when dealing with a new technology, contractors often add an additional fee to insure that the company can turn a profit when installing something that their company has never done before. From a contractor's point of view this is all risk-reward based. With new systems and technologies the contractor is substantially increasing the risk by working on something that could go poorly. Often this difference is based on how fast they think it can be installed and how quickly they can work out any problems that the system is experiencing.

With most everything there is a learning curve that occurs with the installation of a DC microgrid system and if a contractor is new at it they understand that it will take significantly longer than a traditional AC distribution system. This then leads to many contractors pricing these systems well above what it would actually take a contractor with DC microgrid experience to install. In some cases contractors may choose not to bid on jobs such as this where these things are unfamiliar; they begin seeing it as an unnecessary risk if they already have plenty of work. When fewer contractors decide to bid a job there are fewer competitive bids and the owner is often stuck with a higher than necessary bill leaving the owner asking if this system is worth the extra expenditure.

Servicing these systems is often the same story, with fewer contractors willing to work on them the cost increases as the risk for the contractor rises. These cost increases are a very strong consideration to an owner and can cause the proposed system to be cut due to lack of available capital or a poor return on investment.

Initial Cost

The cost increase for a DC microgrid is not only due to the unfamiliarity of the system, they are also part of the direct nature of today's DC microgrid installations. Due to the lack of a standardized plug or devices that use a DC plug, there are often items that will still require a 120V 60Hz receptacle. This and a few other AC loads throughout the building lead to the designer having to install what are essentially two separate power distribution systems in the building. Imagine in a DC microgrid that the designer is trying to provide power for a room that contains both lighting and receptacles. In a traditional AC system the electrical system would have only one circuit headed to the panel and both the lighting and the receptacle are together. In a DC microgrid there would be one DC circuit for the lighting and one AC circuit for the receptacle. Although it is known that in the long run the use of DC in the lighting will pay for the additional upfront cost to provide both AC and DC power to the space, the increase in upfront cost can break a budget for the owner. This happens all over the building and the building has now switched from a DC building to a hybrid building that has two separate power systems serving the space.

This double system is currently a substantial problem that significantly increases the cost of these systems in many applications. Until DC has become more standardized this will continue to be a problem that causes many projects to be cost prohibitive. This leads to fewer of these proposed projects being built and fewer contractors being experienced with the systems, leading to yet a larger increase in price. It should be noted however that this is often disputed due to the smaller total footprint of DC systems in buildings such as data centers. The equipment used for DC distribution is often significantly smaller due to elimination of devices such as power conditioners and transformers. With such a high percentage of DC load, the space saved actually lowered the cost of the system by 20% when accounting for the smaller volume of the building that must be constructed (AlLee & Tschudi, 2012).

Lack of Incentives

With many new projects or ideas, it is often the United States or other governments that provide incentives that get these projects moving forward. Yet for some reason, with these systems there are no incentives available to encourage owners to make this transition.

Renewable energy has long been receiving incentives from both the federal and state governments, so it would only stand to reason that they would incentivize things that would make the use of these generation sources more efficient. It is true however that these systems are, in a roundabout way, being incentivized by the renewable incentive anyway. If there are increased DC sources of power available it helps DC by allowing for additional savings over the double conversion process that accompanies renewables with an AC distribution system. In most of the cases it comes down to the economy of the system rather than government incentive. There have been no indications that would show there are any incentives in the works to promote switching to DC power.

Disadvantages Conclusion

There are many drawbacks associated with the use of a DC microgrid in the current market, however most of these problems can be overcome as these systems become more familiar to contractors and designers. As familiarity is achieved, the system cost should continue to decrease leading to even more familiarity and so on. As with all new technologies it takes time to be adopted and the full potential of the system to be utilized.

Chapter 6 - Current Applications

With limited modeling ability of DC microgrid systems available at this time to document the potential savings, perhaps it would be best served to look into their current applications in today's society. The three case study areas presented are as follows:

- Data Centers
- Commercial
- Residential

For many applications, the DC microgrid has been limited to just DC lighting and the distribution for that lighting. This is a direct result of the DC industry focusing on this development area due to the demand for lighting in all sectors while trying to increase market awareness and beginning to expand scope.

Data Centers

Data centers have been the testing grounds for DC microgrids due to both their high energy demand and their almost entirely DC load profile. Currently, data centers are the areas that most commonly use DC power for things other than lighting.

Data centers at Lawrence Berkeley National Laboratory (LBNL) have recently migrated to a 380VDC architecture from their traditional 480VAC standard. Their experiments have shown that this switch saves anywhere from 10% to 15% in energy consumption depending on the given year. Documented cases such as Sun Microsystems at LBNL have documented savings of over 28% (Downey, 2010).

Researcher's at LBNL estimate that this savings could reach upwards of 20% if changing from 208VAC architecture to the 380VDC. The systems in both cases use a 48VDC bus to feed the server cards (de Jong, 2007).

"Peter Gross, CEO of consulting engineering firm EYP Mission Critical Facilities Inc. reported savings from 10 to 20% by changing to a DC distribution architecture and then being able to effectively replace the AC-DC power converters, with a typical efficiency of 65%, with DC-DC converters with efficiencies in excess of 90 %"(de Jong ,2007).

Data centers have consistently demonstrated savings of over 20% when compared with typical AC distribution architecture and this is without producing onsite power, which would drive the energy savings up higher.

Commercial

A case study was completed on a facility in Rochester, NY that used DC lighting throughout the building, which included 33,000SF of warehouse space and 6,600SF of office lighting. The information in the case study is from (EPRI, 2006).

The facility was equipped with 21kW of PV panels located on the roof of the building and 2.1kW of panels mounted on a canopy at the office entrance.

Their power is distributed in three different ways:

2.1 kW are used in the office lighting

10.5 kW are used for warehouse lighting

10.5 kW is inverted for use in the building or sold back to the utility company

The project was a retrofit in which the fluorescent lamp ballasts were replaced with a DC counterpart provided by Nextek Power Systems. Before the retrofit the lighting density for the two spaces combined was at 1.1 W/SF. After the new DC lighting system was installed the new lighting density was 0.74 W/SF, a significant reduction. The reduction in lighting density is because the W/SF figure includes ballast losses into that calculation. Changing from an AC ballast to a DC ballast was a large factor in reducing the lighting density.

The lower lighting density, combined with a new low voltage control scheme, that allows for daylight harvesting, resulted in an overall power savings of 20% of the original lighting load. The initial cost of the system was $72,000 and if there is an assumed electricity cost of $0.10/kWh their estimated electricity savings were $4000 dollars per year resulting in a simple pay back of 18 years. However, the study shows that shortly after this was adopted the company's rate structure was changed from the initial to include a fee increase for peak usage. The company estimates that their new rate, without the reduction in load, would have been $0.20/kWh. This would reduce the simple payback period to 9 years.

Residential

The following case study consists of a residential complex of 20 apartment units (Kakigano, Monura & Ise, 2010).

The distribution system used in this case study was 400VDC distributed at ±200VDC to all 20 units. The power was used in each home, powering these devices in each unit:

- Washing Machine
- Air Conditioner
- Refrigerator
- LCD TV
- LED Lighting

The DC power came from two sources. The first of which is a 30kW PV array located on the roof and the second is a 6.6kW natural gas cogeneration engine. The PV array is used for power generation only where the engine is used both for the power and the hot water demands of the building. Power distribution units were implemented and loads were either supplied by 48VDC or 24VDC in all cases, except for the air conditioning.

The study first sought out to find the total conversion losses in a one month period. It was found that the conversion losses without the DC distribution were around 6710kWh and with the DC distribution it was reduced to 1030kWh. The losses from the AC power conversions were reduced by 85%.

The study showed that over the course of the year the DC system saved around 15% of the total building electrical consumption, excluding the savings obtained from the cogeneration.

Chapter 7 - Conclusion

With the architecture of the United States electrical gird designed and installed many years ago using standards established over 100 years ago, it would be difficult to have a complete reversal in power distribution in a short amount of time.

Many points have been presented about the electrical efficiency that stands to be gained from implementing DC microgrids in buildings. As the world becomes ever more energy conscious DC microgrids could become an important part of the nation's power infrastructure in the near future.

The efficiency advantages of DC microgrids have been compounded by a shift in energy usage from predominantly AC power just 30 years ago to a society that interacts with DC power every day. As more individuals and companies begin to invest in renewable power sources, DC microgrids increase system efficiency, driving up the net worth of the generation systems.

There are many obstacles to overcome before DC microgrids see widespread use. Codebooks are living documents and the longer DC power is around, DC microgrids will begin to get additional consideration and code clarification increasing contractor and designer comfort. This lack of comfort with DC power along with the relatively high price of systems and generation sources such as PV has kept the return on investment near the upper end of what companies are looking for.

It seems that DC microgrids have many upsides, primarily among them is the efficiency of the conversions in a DC system. This will lead to continued interest from investors, owners, and designers for years to come as the world pushes further into an energy conscious state of mind.

Disadvantages of DC microgrids can easily be overcome with the passing of time and increasing of familiarity. These disadvantages appear to be tied to contractor unfamiliarity and standardization issues. Contractors will become more familiar with these systems as owners and designers make the push for efficient buildings. Standardization issues will perhaps be more difficult and time consuming to overcome but the rate of this progress will be directly proportional to the amount of interest generated on the topic. Although this would require the most time investment for DC power to become standardized, it is the biggest obstacle to overcome in order to promote widespread DC usage. This would result in the removal of the double distribution systems in buildings now, resulting in significantly lower capital costs.

There has been little research done for directly comparing these DC microgrids to their AC distribution counterparts. Most case studies that are available for review are studies that are directly related to remodel work. It is difficult to say how much of this savings is due to increased efficiency in items outside the scope of the case studies. In order to continue the research it seems that the next step is to start building identical buildings with only the electrical distribution varying between structures. This would allow a straight heads up comparison regarding both construction costs and energy efficiency over time, leading to more in depth analysis of DC microgrids.

In conclusion, DC microgrid use will continue to increase with the world becoming energy conscious and it will be interesting to see where this technology can go, even in just the next 10 years. The key to making DC microgrids a widespread reality is to continue the discussion and focus on the long term goal of more efficiently utilizing the energy resources that society has.

Bibliography

AlLee, G. & Tschudi, W. (2012, November/December). Edison redux: 380 vdc brings reliability and efficiency to sustainable data ceters. IEEE power & energy magazine,

Baigrie, B. (2007). Electricity and magnetism: A Historical Perspective. Westport, CT: Greenwood Press.

Cetin, E., Yilanci, A., Ozturk, H. K., Colak, M., Kasikci, I., & Iplikci, S. (2009). A micro-dc power distribution system for a residential application energized by photovoltaic-wind/fuel cell hybrid energy systems. Energy and Buildings, 42,

Downey, L. (2010, 10). Dc microgrids. Darnell smart grid form, San Jose, CA.

EPRI Electric Power Research Institute. (2006). DC power production, delivery and utilization. Palo Alto, CA:

Jiayi, H., Chuanwen, J., & Rong, X. (2007). A review on distributed energy resources and microgrid. Renewable and Sustainable Energy Reviews, 12,

Jonnes, J. (2003). Empires of light: Edison, tesla, westinghouse, and the race to electrify the world. (1st ed.). New York, NY: Random House.

Justo, J. J., Mwasilu, F., Lee, J., & Jung, J. W. (2013). Ac-microgrids versus dc-microgrids with distributed energy resources: A review. Renewable and Sustainable Energy Reviews, 24,

Kakigano, H., Nomura, M., & Ise, T. (2010). Loss evaluation of dc distribution for residential houses compared with ac system. The 2010 international power electronics conference.

Leonardo ENERGY. (2007). DC power distribution for server farms. E.C.W. de Jong & P.T.M. Vaessen.

McNichol, T. (2006). Ac/dc the savage tale of the first standards war. (1st ed.). San Francisco, CA: Jossey-Bass.

Meyer , H. W. (1972). A history of electricity and magnetism. Norwalk, Connecticut: Burndy Library.

Okba, M.H.; Saied, M.H.; Mostafa, M. Z.; Abdel- Moneim, T. M., "High voltage direct current transmission - A review, part I," Energytech, 2012 IEEE , vol., no., pp.1,7, 29-31 May 2012

Patterson, B. T. (2012, November/December). Dc, come home. IEEE power & energy magazine, 60-69.

Savage, P., Nordhaus, R. R., & Jamieson, S. P. (2007). Dc microgrids: Benefits and barriers. Yale School of Forestry & Environmental Studies.