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DC Microgrids Scoping Study—Estimate of Technical and Economic Benefits

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Contents

1. Executive Summary

Motivation: Microgrid demonstrations and deployments are expanding in US power systems and around the world. Although goals are specific to each site, these microgrids have demonstrated the ability to provide higher reliability and higher power quality than utility power systems and improved energy utilization [1] [2][3]. The vast majority of these microgrids are based on AC power transfer because this has been the traditionally dominant power delivery scheme. Independently, manufacturers, power system designers and researchers are demonstrating and deploying DC power distribution systems for applications where the end-use loads are natively DC [4], e.g., computers [5], solid-state lighting [6], and building networks [6]. These early DC applications may provide higher efficiency, added flexibility, reduced capital costs over their AC counterparts. Further, when onsite renewable generation, electric vehicles and storage systems are present, DC-based microgrids may offer additional benefits [7]. Early successes from these efforts raises a question—can a combination of microgrid concepts and DC distribution systems provide added benefits beyond what has been achieved individually?

Scope: The intent of this study is to provide a preliminary examination of the benefits and drawbacks of potential DC microgrid applications relative to their AC counterparts and to provide recommendations for potential future research and deployment activities. The performance of notional AC and DC microgrids are estimated and compared using several metrics:

1. safety and protection
2. reliability
3. capital cost
4. energy efficiency
5. operating cost
6. engineering costs
7. environmental impact
8. power quality
9. resilience.

Several types of AC and DC microgrids applications were compared. The initial comparison is done using several generic microgrid architectures to reveal the importance of and to initially screen the different metrics. Then, several specific microgrid applications are considered to draw out possible unique advantages of DC over AC microgrids. These applications include:

1. DC Microgrid as an Efficient, Low-Cost Platform for Economic (Steady-State) Integration

2. High Survivability DC Microgrids

3. Low Power Network with Differentiated and Automatically Evolvable Power Quality and Reliability

4. Converting AC Systems to Hybrid AC/DC Systems

5. Mobile and Remote Applications

6. Data Center Support Systems

7. Coupling a DC Microgrid to a HVDC Line

8. Electric Vehicles for Backup/Emergency Power.

We note that the assessment of the general architectures and specific applications is done using the best estimates of the performance and cost of commercial or near-commercial technology. It should be noted that several emerging technologies could change the conclusions and recommendations of this study. The most prominent of these technologies is the use of wide bandgap semiconductors in high-power applications such as rectifiers and DC-DC converters. Significant improvements enabled by these semiconductors include higher reliability from fewer junctions per device and availability of both AC and DC buses from a single power electronic device.

Recommendations: Analysis of the generic microgrid architectures and the specific applications against the study metrics leads to two applications recommended for immediate further study and a third for potential study in the future:

1. **DC Microgrid as an Efficient, Low-Cost Platform for Economic (Steady-State) Integration**—Many new distributed energy resources are direct DC, e.g. photovoltaic (PV) generation, stationary batteries, mobile batteries, and

fuel cells. Also, many high efficiency loads are also direct DC [4]. A microgrid utilizing a DC bus may avoid many of the power conversion steps required when using an AC bus, potentially leading to higher energy efficiency and improved economic operation for DC microgrids. However, these benefits need to be carefully weighed against the potentially higher cost of interfacing a DC microgrid to the bulk AC power systems. To provide more accurate estimates of these costs and benefits, this scoping study recommends a more detailed simulation-based study of comparable AC and DC microgrids that, at a minimum, accounts for the following factors:

(a) realistic microgrid load and generation profiles (daily and annual)

(b) the use of realistic AC-DC, DC-AC, and DC-DC power conversion efficiency curves that account for the typical decrease in efficiency at part load

(c) fair and detailed treatment of the conductor losses in AC and DC microgrids including the effects reactive power flow and mitigation of losses through additional capital expenditures on conductors.

(d) sensitivity of the reliability of DC microgrids (i.e. the ability to deliver power to the microgrid loads) to the sizing of the power electronics at the AC-DC interface to the bulk power system and the sizing of microgrid's distributed energy resources.

(e) at equivalent reliability, the sensitivity of the economic performance of DC microgrids to the sizing and capital cost of the microgrid energy resources and power electronics at the AC-DC interface to the bulk power system, including the impact of this sizing on the ability of the DC microgrid to export power to the bulk AC system

We emphasize that all of the assessments and effect mentioned above should be done using realistic load and generation profiles, not peaks or averages. The main objective of the recommended study is to provide accurate estimates of the economic performance of AC and DC microgrids for designs that yield equivalent reliability, where reliability is considered in the N-1 sense of being able to serve all critical load after the loss of any one component.

2. **High Survivability DC Microgrids**—Microgrids are subject to many different types of internal and external disturbances. To be ”survivable”, the

post-disturbance microgrid dynamics should converge to steady-state operation with no loss of critical load and minimal loss of non-critical load. The sources in a DC microgrid only have to reach a steady state DC voltage whereas an AC microgrid's sources must achieve a steady state voltage magnitude and frequency. The power electronics at the AC-DC interface may shield DC microgrid dynamics from many external disturbances leading to higher survivability. For internal disturbances, the fewer dynamical states of the DC microgrid may lead to simpler controls, may make achieving the new steady state easier and potentially lead to improved survivability. A greater immunity to external and internal disturbances could lead to higher reliability and lower engineering costs. To provide a better estimate of these potential survivability benefits, this scoping study recommends a more detailed simulation-based study of comparable AC and DC microgrids that, at a minimum, accounts for the following factors:

(a) for the AC and DC systems, equivalent bus, line, and source architectures that include at least two buses with a mix of sources at each bus, e.g. two DC direct sources (e.g. one PV generator and one battery) or one DC direct source and one AC native source (e.g. a natural gas-fired rotating machine). These sources should be interfaced to the microgrid bus as appropriate for type of system under consideration.

(b) realistic and comparable tripping conditions for both the DC-direct and AC-native generation sources

(c) potential differences between unipolar and bipolar DC microgrid configurations

(d) equivalent internal and external disturbances that include a range of extreme but plausible cases, including:

   i. outage of the AC grid at the substation supplying the microgrid with subsequent (delayed) microgrid islanding

   ii. fault on the AC grid near the interface to the microgrid with subsequent (delayed) microgrid islanding

   iii. faults on the microgrid buses that are cleared with and without isolating the the faulted bus

   iv. large changes in microgrid load while grid connected and islanded with large changes in motor load likely being the most severe.

The performance of the AC and DC microgrids should primarily be judged on their ability to maintain service to critical loads following the disturbance with a secondary consideration of the cost of the control system, generation sources, and power electronics. The survivability study may want to consider using the same microgrid architectures as in the "Low-Cost Platform" study for comparison.

3. **Low Power Network with Differentiated and Automatically Evolvable Power Quality and Reliability—**These networks and microgrid are generally low voltage Power Over Ethernet (PoE) systems where communications and power distribution are naturally integrated into the same wiring and switching. The integrated architecture and communications protocol naturally enables end device self identification with the potential for automated network or microgrid reconfiguration. At current device power levels, it is not clear if these networks will ever achieve the minimum power threshold used in this study and become large enough to be relevant to DOE Office of Electricity. However, the rapid evolution in this area justifies continued monitoring of this technology.

Ancillary Benefits This scoping study makes a fundamental assumption that the decision to convert from traditional AC to significantly more efficient DC loads [4] (DC-internal in the case of an AC architecture) is independent of the decision to convert from an AC architecture to a DC architecture. Although is allows for a clean analysis of the benefits of the DC versus AC architectures, the human factors behind the decision to use efficient DC loads are less "clean". Promoting DC architectures may be a path to the conversion to DC loads and their inherently better energy efficiency.

2. Introduction

Because AC traditionally enabled efficient voltage transformation and high voltage power transmission over long distances, it dominated our bulk power system, and consequently so much of what lies downstream of it. Technology advances, however, have led to highly efficient AC/DC and DC/DC converters, which have made high-voltage DC a more efficient means for long-distance bulk power transmission[8]. At the same time, parts of the electricity system are evolving towards local generation, storage, and use, where the majority of the local generating sources and loads produce and consume DC power. While the everyday power supply in our factories and buildings is AC, DC power systems are becoming commonplace and ubiquitous, such as in building communications and IT networks, building automation and fire life safety and security systems, onsite renewable power generation, onsite storage, remote homes, vehicles, vessels, aircraft, and powering remote communications devices.

The basis for AC as the sole platform is eroding and reevaluation is timely. Compared to AC power, the distribution of DC power over DC networks has *potential* to provide several benefits to equipment manufacturers, electricity customers, electrical systems, and the environment including but not limited to:

- higher power system efficiency because of fewer AC-to-DC, DC-to-AC, or AC-to-AC power conversions in local power systems that include a significant amount of distributed generation or storage that naturally produce DC power

- higher reliability in those same systems because fewer power conversions require fewer power electronic components, with fewer potential points of failure

- lower capital cost because of fewer power electronic components and potential reductions in conductor cost because DC allows higher current carrying capability

- a potential for lower control system complexity and higher survivability when subject to external and internal disturbances because of the elimination of synchronization requirements of AC systems.

- higher power quality and disturbance survivability because of the power electronics and (potentially) storage buffer between the DC microgrid and the AC grid.

- "Managed DC" technologies have communications integrated with power enabling control and configuration capabilities not present with today's AC technology.

The promise of these benefits has spurred several demonstrations of DC networks, especially in data centers and commercial buildings, with some of these demonstrations providing evidence for subsets of the benefits listed above. An excellent summary of these projects can be found in [6] and the reference contained therein.

Less clear are the added benefits of a DC microgrid, i.e. the aggregation of DC generation sources, storage, DC loads, etc., by a DC power distribution network to form a single controlled grid that provides more benefit than just the gains from a passive DC network.

Scoping Study Objectives The objectives of this study are to describe applications where DC microgrids may have advantages over their AC counterparts, estimate the benefits or drawbacks for these applications, **consider how these applications could be combined into more comprehensive DC microgrid systems, and estimate the market potential of these conceptual DC microgrid systems.** In the discussion of the DC microgrid applications, the total benefits are to be compared to those from traditional AC service or microgrids.

2.1 Terminology

The discussion of the DC microgrid devices and applications will benefit from a common terminology, which is defined here:

- AC load—An electrical load that interfaces with an AC power system and uses the AC current/voltage directly, e.g., a fixed speed induction motor.
- DC-internal or native-DC load—An electrical load that interfaces with an AC power system but converts the AC current/voltage to DC, which is then used for powering the device, e.g. the majority of electronic devices, most compact fluorescent lighting , and variable speed motor drives.
- Direct-DC load—An electrical load that interfaces with a DC power system and uses the supplied DC current/voltage directly or may include a

DC-to-DC conversion step to obtain an acceptable DC voltage, e.g., light-emitting-diode lighting and DC motors in air conditioning, heat pumps, and refrigerators.

- DC-to-AC converter/inverter—A power electronics device that converts DC voltage/current to AC voltage/current compatible with standard AC power systems.

- DC-to-DC converter—A power electronics device that converts one DC voltage/current to a different DC voltage/current, e.g., 380 Vdc to 48 Vdc.

- AC-to-DC converter/rectifier—A power electronics device that converts standard AC voltage/current to a DC voltage/current.

- Managed DC—Standard DC technologies that include communications for managing power distribution within the power cable (over the power wires or over adjacent wires). The most common examples today are Universal Serial Bus (USB) and PoE.

- DC Network—A power system that transmits electricity in the form of direct current. DC sources and loads are connected to the network either directly or through DC/DC converters. AC sources and loads are connected through AC/DC converters and DC/AC inverters, respectively. The DC network is connected to the AC power system over a bidirectional AC/DC converter and it can either withdraw or inject power to the AC grid.

- DC Microgrid—A DC network enhanced with advanced capabilities that enable control of DC network resources for higher operational performance and/or the ability to operate independently of the primary AC system for enhanced reliability. For this scoping study, the DC microgrid should have a minimum 100 kW capacity of aggregated source capacity.

- Low Voltage DC—Less than 50 V_{DC} which includes DC applications in telecom, LED lighting, USB, and PoE and in at least one standard under development [9].

- High Voltage DC—Between 300 and 400 V_{DC} which is consistent with most power distribution systems in DC data center applications [5] [6] and in at least one standard under development [9]

- Utility Voltage DC—Voltages typically used by electrical distribution utilities to transmit power from a substation of a customer's service transformer, e.g. 4-35 kV.

- Firm Generation—Electrical generation that is controllable and dispatchable such as a Diesel generator, combined heat and power (CHP) generation, or battery storage.

- Non-Firm Generation—Generation that is uncontrolled or has limited controllability such as PV or wind generation.

2.2 Metrics For Assessing the Impacts of DC Networks and Microgrids

Assessing the total impacts (both positive and negative) of a DC microgrid beyond a traditional AC system or AC microgrid requires a common set of metrics. The metrics considered in this study are introduced below and are discussed in greater detail in Section 3.

- Safety and Protection—The ability of the power system to prevent injury to people and protect equipment from damage

- Reliability—AC power system reliability is typically measured using metrics such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) [10] that measure the customer-averaged outage duration and interruption frequency, respectively. This study reinterprets these metrics with a focus on the reliability of power supplied to individual loads or load classes within microgrids.

- Capital Costs—Total equipment and installation costs for the microgrid as incurred by the owner of the microgrid. The distribution utility that serves a DC microgrid may also see capital cost benefits. However, it is not clear how the microgrid owner could monetize these benefits, and these benefits to the greater system are not considered here.

- Energy Efficiency—Measured at the system level, the total input electricity required to serve an end use function. For the ownership model considered in this study, the system boundary is at the micrgrid to local grid interface.[1]

- Operating Costs—Present value of total variable cost (primarily energy use, but also including ancillary revenue streams, maintenance, etc) for a power system to serve an end use function.
- Engineering Costs—Site specific engineering costs to integrate the components of the microgrid with each other and the microgrid to the surrounding power systems.
- Environmental Impact—The total CO_2 emissions produced by marginal electricity generator used to deliver the net electrical needs at the interface of the microgrid and the local power system.
- Power Quality—The ability of a AC or DC microgrid to stay within its respective Computer Business Equipment Manufactures Association (CBEMA)/Information Technology Industry Council (ITIC) curve for a given type of disturbance.
- Resilience—Ability to serve electrical load when the main AC grid is unavailable for extended periods of time, e.g. for typical multi-day outage times following major natural disasters such as hurricanes or earthquakes [11]

We note that, in several cases, there is insufficient data or analysis available to provide a quantitative assessment of these metrics. In these cases, a qualitative assessment is given if there appears to be a clear advantage of a DC microgrid over a traditional AC system or AC microgrid.

2.3 Microgrid Reference Architectures

The DC microgrid applications proposed in Section 5 are only a subset of the possible applications, and each of the proposed applications could utilize several different architectures. Prior to analyzing these applications in detail, Section 3 analyzes the representative generic architectures in Figure 2.1 absent a specific application, which provides a foundation for the analysis of specific applications in Section 5.

[1]Note that this study does not include some of well known energy efficiency effects, e.g. the reduction in air conditioning load because of higher end use efficiency, because of the assumptions made about the use of DC-internal loads in AC microgrids.

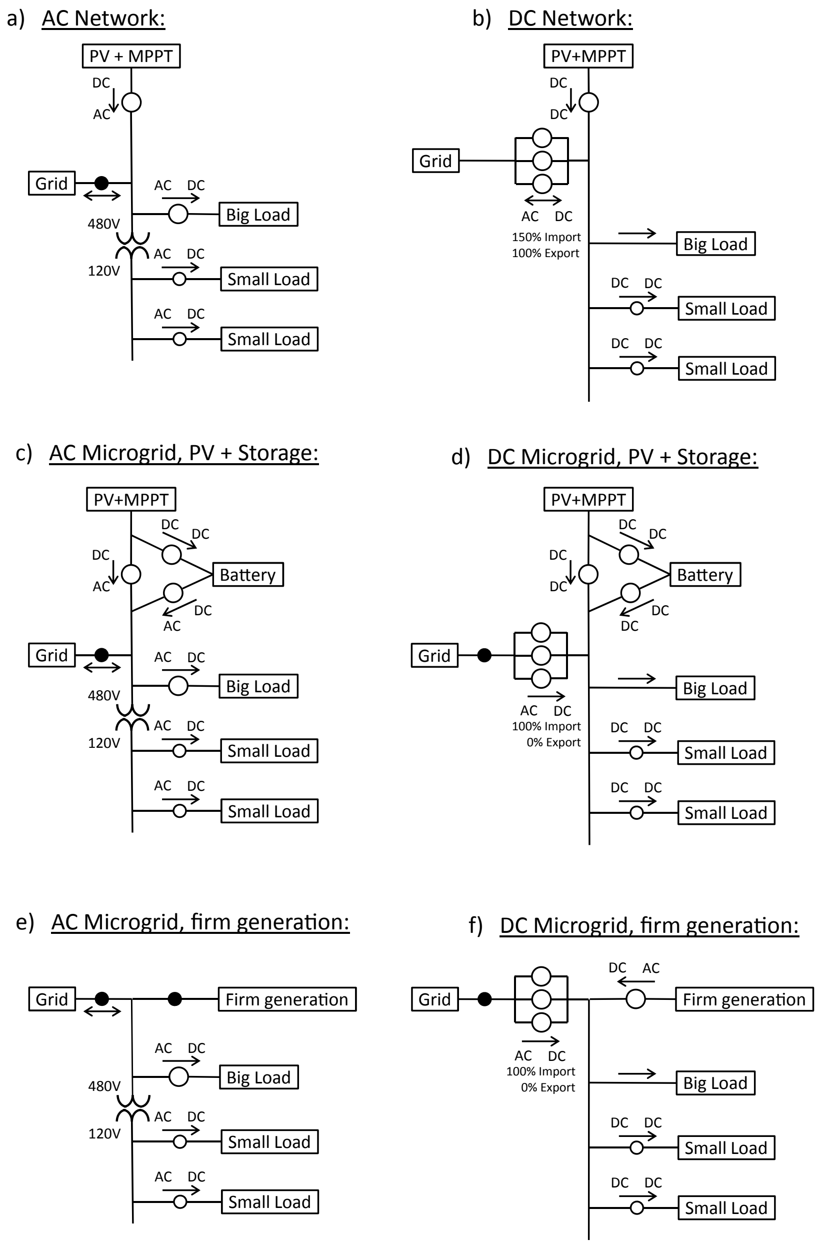

Figure 2.1: Six power system reference architectures. Open circle: voltage converter, rectifier, or inverter. Filled circle: switch. Arrows: direction of power flow. All loads are assumed to be native-DC. The percentages listed under the power electronic interface at the AC grid/DC microgrid point of common coupling indicate the capacities of the importing and export electronics relative to the peak microgrid load.

Figure 2.1 displays schematics for the six different power system reference architectures considered here in this work.[2] We note that these architectures are very similar to those used in [7] . There are some common architectural assumptions shared by these different reference architectures (which should be revisited for each application in Section 5):

- At a minimum power level of 100 kW, the AC systems will likely be three phase power systems, and the analysis of the architectures in Figure 2.1 will assume a three-phase configuration. The DC systems could be unipolar or bipolar, however, at these power levels, the main wiring is expected to be bipolar.

- The microgrids are connected to the AC power grid at a 480V/277Y voltage level appropriate for a 100 kW load center.

- Both the AC and DC microgrid systems include a switch at the point of common coupling (PCC) to disconnect the microgrid from the AC grid.

- Other studies [4][6] have concluded that the conversion from AC loads to DC-native or DC-internal loads provides significant energy efficiency benefits. *To ensure that the comparison of AC and DC systems in this study is not biased by the use of these higher efficiency loads in DC systems, we assume that all loads are native-DC, and the AC systems will require an AC-to-DC conversion step.* Under this assumption, the losses at the loads are very similar, eliminating energy efficiency gains due to secondary effects like lower thermal loading on air conditioning.

- The DC-native loads are split into two categories—"Big Loads" that operate off of a nominal DC bus voltage of 380 V and "Small Loads" that operate off of a nominal 24 or 48 V. For the purposes of the estimates in this study, we will assume a 50/50 split between the Big and Small load classes.

- In the AC microgrid, a 75 kVA transformer is included to reduce the voltage from 480V to 120V before serving the "Small Loads".

[2] We note that these reference architectures are not intended to represent a power system serving the compute load of a large data center because this application is already well addressed by several industry demonstrations. These demonstrations and one controlled laboratory study by Lawrence Berkeley National Laboratory have demonstrated the energy efficiency benefits and potential reliability benefits of a DC power system for this application. A summary of these demonstrations can be found in [6] and citations therein.

- In the AC and DC microgrids with PV generation and battery storage, the battery system is assumed to be integrated with the PV system. In Figure 2.1, the three converters in this integrated subsystem are often lumped together as a "charge controller". Here, we split these out to account separately for losses in each conversion.

- We note that an equally valid architecture would interface the PV and battery subsystems separately enabling the battery to charge directly from the microgrid bus adding more flexibility to the operations. The main change to the analysis discussed later in this report is a minor shift in the round trip efficiency for battery charging/discharging (1% lower round trip efficiency for the AC architecture). This minor difference does not change the conclusions of the analysis of the generalized architectures.

- For the AC microgrids without firm generation, the DC-AC inverter on the storage or PV will have to be an "off-grid" inverter capable of supplying the reactive power needs of the microgrid and capable of regulating this reactive power to control voltage while islanded. The firm generation is assumed to be synchronous generation and capable of reactive power support.

The sizing of the sources in Fig. 2.1 is independent of the architecture and will likely depend on the specific application under consideration. *We note that these sizing assumptions directly affect capital cost of the component being sized and can indirectly affect sizing and capital cost of the other components. The effects on economic performance are important and should be investigated in much more detail in follow on work.* Here, we discuss a few assumptions and issues surrounding the sizing used in the analysis of the generic architectures in Fig. 2.1:

- The AC and DC networks and microgrids may include distributed PV generation. For the purposes of the simplified analysis in this study, the daily *energy* output of the PV generation is assumed to be matched to the daily *energy* consumed by the loads.

- Instead of PV generation, the architectures could also include wind generation or other forms of intermittent generation. However, under the assumptions above, this modification would not materially change the outcome of this simplified analysis.[3]

[3]However, the effects of the change in the daily and annual generation profile from different mixes of intermittent renewable generation requires detailed study in follow on work.

- The AC and DC microgrids may include some form of firm generation that is fully dispatchable and is *not* energy limited. For the purposes of this simplified analysis, the firm generation is sized so that it can supply the peak load in the microgrid.[4]

- The AC and DC microgrids with PV generation also include battery storage. For the purposes of the simplified analysis in this study, the storage energy is sized so that it can meet the daily energy consumed by the loads, and the storage power is sized to meet the peak load in the microgrid. This assumption enables the microgrids to serve their loads even during extended outages, such as those implied by the resilience metric of Section 2.2, when availability of PV or wind generation becomes suspect.

- For DC microgrids, the sizing of the bi-directional converter/inverter interface to the AC power system, when coupled to the sizing of the other microgrid components, is critical to the microgrid reliability. Here, we consider architectures in Figs. 2.1b), d), and f) separately:

  - DC Network (Fig. 2.1b)—The "failure" of the PV system to produce sufficient power and energy to support the network loads is far more likely than an N-1 failure. During these times, the DC Network is completely dependent on imports from the AC system and the AC-DC converter must be able to withstand a single failure at this interface. Therefore, the AC-DC import power electronics must be composed of at least three separate devices each sized to supply one-half of the total load in the system. The sizing of the DC-AC export power electronics will depend on the overlap of the PV generation and network load – ranging from zero capacity for perfectly *matched* generation and load to full PV capacity (i.e. the DC Network load) for completely *disjoint* generation and load.
  - DC Microgrid, PV+Storage (Fig. 2.1d)—The addition of storage (sized as discussed above) to the PV generation provides a significant reduction in the likelihood that the combined system will not meet the power and energy requirements of the microgrid load. Oversimplifying, we assume that the loss of the PV+Battery system now constitutes an N-1 failure. Therefore, the AC-DC import capacity can be reduced to

[4] For the "firm generation" architecture in Fig. 2.1e) and f), this assumption does not require additional investigation. However, if the firm generation is mixed with other sources, e.g. intermittent PV or wind, further investigation of the sizing is warranted.

100% of the microgrid load as opposed to 150% of the microgrid load. The presence of the battery now enables the PV generation to be managed so that exports to the AC system through the DC-AC interface are likely not required, and we eliminate these components here.

– DC Microgrid, firm generation (Fig. 2.1f)—The failure of the firm generation constitutes and N-1 failure, so like the PV+Storage case, the AC-DC import capacity is set to 100% of the microgrid load. Determining the DC-AC export capacity is difficult because the reasons for running the firm generation may go beyond the need for electrical power in the microgrid, e.g. if the firm generation is CHP and the thermal loads do not overlap with electrical loads. However, to simplify the analysis, we set the export capacity to zero like in the PV+Battery case.

2.4 Operating Modes and Load Profiles

The total power lost in the conversions depends on the energy[5] that passes through the different devices which in turn depends on the relative timing of the microgrid generation and load [7]. Two extreme "corner cases" are considered here: 1) perfectly *matched* generation and load profiles and 2) generation and load profiles that are completely *disjoint*. Load and generation profiles that fall between these two extremes can be analyzed by taking linear combinations of these two results. In the disjoint case, we assume the battery and firm generation (when present) are controlled so that power flow back to the AC grid is eliminated and no DC-AC power conversion (or capital cost of this equipment) is required.

[5] The efficiency of the power conversions depends on the fractional loading of the devices. This effect has been accounted for in detailed simulation and analysis of AC and DC architectures [7]. This study considers a simplified setting where the power conversion devices are always operating near to their peak efficiency so that the total losses can be based only on energy exchanges. This scoping study recommends a more detailed follow-on study accounts for realistic load and generation profiles as well as realistic part-load efficiency curves for the power electronic conversions.

3. Analysis of Microgrid Metrics

Before considering specific DC microgrid applications in Section 5, we first analyze the metrics of Section 2.2 using the reference architectures of Section 2.3. The applications in Section 5 can be analyzed relative to these reference architectures.

3.1 Safety and Protection

Low voltage DC The safety of people around and the protection of equipment within a DC microgrid is crucial to its success. These properties are also dependent on the voltages used in the DC microgrid. The EMerge Alliance standard for occupied spaces [9] specifies 24V for final distribution of power to lighting and other low-power devices. When individual 24V DC circuits are limited to 100VA, they qualify as Class 2 and are considered intrinsically safe from shock or fire hazard [12]. At a somewhat higher voltage, the telecom industry has used 48V DC systems for many years. In either case, there do not appear to be any significant unresolved issues regarding safety and protection for distribution of power at these voltages.

High voltage DC To reduce loss and serve larger loads, many of the data center demonstrations utilize a higher voltage DC distribution in the range of 350-400 V, with 380 V being very common [5][6]. For these data center and other general purpose applications, several companies supply DC power distribution hardware including circuit breakers [13] with rated currents ranging from 15A to 2500A [14].

The conclusion of the brief review in this Section is that safety and protection metric does not provide a significant advantage to AC or DC microgrids. Therefore, for the purposes of this study, *the "Safety and Protection" metric from Section 2.2 is not a major distinguishing factor in the applications in Section 5*, unless an unusual system configuration arises.

3.2 Reliability

Data on the reliability of directly comparable AC and DC systems is rather sparse, but for the case of large data centers, there are studies [5] that report several order of magnitude increases in reliability of DC-powered data centers as compared to AC-powered data centers. However, the reasons identified for the increase in reliability are all data center specific except for one—reduction in the overall *power electronic* component count and/or the reduction in the number of *power electronic* conversion steps [5, 6]. This study evaluates reliability from the same point of view.

If we consider the architectures in Figure 2.1 and compare the AC systems with their DC counterparts, we find three primary differences:

- The DC systems require large power electronic devices at their interface to the AC grid. In the architectures of Fig. 2.1, these devices (for both import and export) have been appropriately sized in coordination with the other energy resources in the microgrid to ensure that these architectures have an N-1 reliability nearly the same as their AC counterparts.

- In the **PV and battery subsystem**, the AC systems have two DC-AC inverters and one DC-DC converter versus three DC-DC converters in the DC system. However, the part count/power conversion step count is the same in the AC and DC systems

- The **firm generation subsystem** is assumed to be some form of fuel-driven rotating generation, e.g. natural gas-fired combined heat and power engine. In this case, the DC system requires an additional AC-DC converter to interface the firm generation with the DC bus. For a failure of this converter to count against the reliability of service *to the loads*, the DC microgrid would have to be in an N-2 state, i.e. the AC grid has failed and the AC-DC converter has failed. The likelihood of such a failure is very low, and we do not count this against the reliability of the DC microgrid with firm generation.

- For the **Big Loads**, there is an additional AC-DC converter in the AC system

- For the **Small Loads**, there is a switch from AC-DC converters in the AC systems to DC-DC converters in the DC systems. However, this does not change the part count/power conversion step count.

- Although not a power electronics component or conversion, there is an extra transformer for the AC systems. However, the cost of providing full redundancy for this transformer is relatively small [15].

From this discussion, we conclude that the main difference in reliability *for service to the loads* between the AC and DC systems is the addition of one AC-DC converter for each Big Load in the AC systems. If any of these Big Loads

Component	Cost Estimate
DC-AC grid-tied inverter (100 kW) [16, 17]	\$0.40/kW
DC-AC off-grid inverter (100 kW) [18, 17]	\$1.60/kW
AC-DC rectifier (100 kW) [19]	\$0.41/kW
DC-DC converter (10 kW) [20]	\$0.35/kW

Table 3.1: Estimates of the capital cost of major power electronics components on a per capacity basis. The DC-AC off-grid inverter is capable of providing reactive power and controlling voltage while the DC-AC grid-tied inverter provides real power at a nominal power factor of 1.0.

were a critical load, this AC-DC converter would have be backed up or, at the very least, a spare have to be kept in inventory. In either case, this reliability issue is again turned into a capital cost issue. The conclusion of the brief review in this Section is that the reliability metric does not provide a significant advantage to AC or DC microgrids. Therefore, for the purposes of this study, *the "Reliability" metric from Section 2.2 will not play a major role in judging the applications in Section 5*, unless an unusual system configuration arises.

3.3 Capital Cost

Capital cost is broken down into two main categories, the cost of the power conversion electronics and other major equipment (e.g. switches) and the cost of the other materials needed to install the power systems.

Power Electronics Table 3.1 provides estimates of the per kW cost of the four basic power electronic conversion devices used in the AC and DC reference architectures in Fig. 2.1. These are generally based on $\sim$100 kW components, and we assume that these per kW costs also apply to smaller components when purchased in quantity. For DC architectures, the cost of any bidirectional power conversion components is assumed to be equal to the sum of the cost of the individual unidirectional components.

The total power electronics costs for the architectures in Fig. 2.1 is roughly estimated based on the load and generation capacities. The total peak load P_{max} is evenly split between the two load classes, i.e. $P_{max}/2$ of "Big" and "Small" loads. Any power converters supplying these loads are sized accordingly. All power converters associated with either PV generation, Firm generation, or the Battery

Architecture	AC Power Elec. Cost	DC Power Elec. Cost
Network	\$81,000	\$154,000
PV + Storage	\$276,000	\$163,500
Firm generation	\$41,000	\$99,500

Table 3.2: Estimates of the total capital cost of the major power electronic devices in the AC and DC power system architectures in Fig. 2.1. In these estimates, the total system load P_{max} is set to 100 kW. Costs of the individual components used in these estimates are given in Table 3.1.

are sized at P_{max}. Finally, the AC-DC import and DC-AC export capabilities for the DC architectures is based on the previous discussions of reliability and are given in the notations in Figs. 2.1b), d), and f). The total power electronics costs are given in Table 3.2 where P_{max} is set to 100 kW.

A brief discussion of the differences between the AC and DC architectures is given below:

- Network—In the Network architecture, the flows between the DC network and the main AC grid are not controlled and the interface power electronics are required to be bidirectional and sized to accommodate an export of P_{max} and an import of 1.5 P_{max} for reliability. All of this extra power electronics capacity at the interface accounts for the bulk of the difference between the \$81,000 cost of power electronics for the AC Network and the \$154,000 cost for the DC Network.

- PV+Battery—In the PV+Battery architecture, the battery is used to manage the flows between the microgrid and the main AC grid. Although the DC microgrid still requires an AC-DC import capacity for reliability, this capacity is reduced from 1.5 P_{max} to 1.0 P_{max} because of the presence of the battery. Also, the battery eliminates the need for DC-AC export capacity. The reduction in the power electronics capacity at the AC grid-to-DC microgrid interface would put the AC and DC architecture on near equal cost footing, however, the AC microgrid requires at least one inverter that can supply reactive power. Our simplified analysis assumes that the battery provides all of the reactive power driving up its cost by \$120,000 and accounting for the large increase power electronics cost of the AC architecture (\$276,000) over the DC architecture (\$163,000). This cost differential could likely be reduced in half to $\sim$\$60,000 by better matching the reactive capability of the battery inverter in the AC architecture to the loads, and such a detailed design is recommended for the follow on study.

- Firm Generation—The firm generation is assumed to be composed of rotating machinery that does not require power electronics to interface it to the AC architecture, whereas a rectifier is needed to interface it to the DC architecture. This extra rectifier accounts for the majority of the difference in power electronics cost between the AC ($41,000) and DC ($99,500) architectures.

The rough estimates of the costs in Table 3.2 show that DC architectures perform better when integrating distributed energy sources that are DC-native (i.e. PV and Battery instead of synchronous machine-based firm generation) and when microgrid controls are used to manage the interface flows between the microgrid and the bulk AC system so that this interface can be made unidirectional (i.e. AC-DC import only).

Both AC and DC microgrid systems will require a utility-grade disconnect switch and/or protection at the point of common coupling (PCC) to the main AC grid. However, both AC and DC microgrids will likely require a method for quickly disconnecting from the main AC grid for AC outages or other disturbances. For the DC microgrid, the power electronics interface will probably be sufficient, however, the AC microgrid will need an additional fast disconnect switch. If an electromechanical switch is used at the PCC, the cost will be insignificant compared to the power conversion equipment, however, the transient performance of the AC microgrid maybe impacted by the slower switching times.

Other materials and equipment The detailed design and cost of the customer-facing components of the power system, e.g. outlets, plugs, etc, will vary too greatly between applications and are beyond the scope of this study. Instead, we make some rough parametric estimates of the cost of materials for the major distribution of power, i.e. at the $\sim$ 380V DC level and at the 480Y/277V AC level.

The 380V DC system, is a three conductor system—+380V, -380V, and neutral. The installed load is assumed to be nominally balanced between the two polarities, but the neutral is sized the same as the hot conductors. The required ampacity is $\sim$130 A. Oversizing by 25% results in an ampacity of $\sim$ 165 A for three conductors requiring the use of 2/0 copper conductors rated at 75°C [21]. At a cost of $\sim$ \$3.60/foot[22], the total cost of the conductors is $\sim$ \$10.60/foot.

The 480Y/277V AC system is a four conductor system—three phase conductors at 277 V relative to the neutral conductor. The installed load is again nominally balanced between the three phases, and the neutral is again sized the same as the phase conductors. In contrast to the DC system, we must account for the flow of reactive power due to a power factor (PF) less than 1.0. After oversizing by 25%, the required ampacity as a function of PF is $\sim$ (150 A)/PF. The AC architectures in Fig. 2.1 include native-DC loads, therefore their reactive power needs from the main AC bus is expected to be rather low. Using a power factor of 0.8, the required ampacity is $\sim$ 190 A requiring the use of 3/0 copper conductors rated at 75°C [21]. At a cost of $\sim$ \$4.56/foot [22], the total cost of the four conductors is $\sim$ \$18.25/foot.

Because of the reactive power requirement, voltage level, and conductor configuration, the conductor cost in the AC system is estimated to be $\sim$ \$8/foot higher than in the DC system. The length of the conductor runs is very system dependent. Using 2000 feet as a nominal length, *the cost reduction in the DC system is $16,000—a reduction that is not expected to dominate the comparison of AC versus DC architectures.*

3.4 Energy Efficiency

In Section 2.3, the different architectures in Fig. 2.1 were put on an equal footing by populating them with the similar energy efficient loads, i.e. native-DC loads for the AC system and direct-DC loads for the DC system [4]. This assumption was made to focus on the difference between AC and DC architectures without biasing the results by an independent choice of the type of loads to install. Conductor losses are another source of losses that could distinguish AC and DC systems, however, the sizing of the copper conductors in the previous Section was done using the same methodology for the AC and DC systems and included the effects of power factor in the AC system. Therefore, we expect similar losses in the AC and DC systems.

Under these load and conductor choices, the power electronics-based conversions (including those required by the use of internal-DC loads) and AC transformers are the remaining major sources of power loss in both the AC and DC reference architectures and form the basis for the analysis of the relative energy efficiencies of these architectures. The device efficiencies used in this study are given in Table 3.3 and nominally correspond to the peak-load efficiencies.[1] Ta-

[1]The use of peak-load efficiency rather than an efficiency-load curve biases the results of this

Input Voltage	Output Voltage	Power	Symbol	Value	Used For
DC High	DC High	High	e_{DC-DC}	0.976	MPPT, Charge controller
DC High	DC Low	Low	$e_{sl,DC}$	0.960	DC bus to small loads
DC High	AC High	High	e_{DC-AC}	0.976	Battery or PV to AC bus,
AC High	DC High	High	e_{AC-DC}	0.965	AC bus to large DC loads
AC High	AC Low	High	e_{AC-AC}	0.985	AC 480V-120V transformer
AC High	DC Low	Low	$e_{sl,AC}$	0.950	AC bus to small DC loads

Table 3.3: Representative peak-load conversion efficiencies of individual power electronic devices in the architectures of Fig. 2.1. Justification of these efficiencies is provided the Appendix and is based on [23, 24, 25, 26, 27]

ble 3.4 also provides the efficiency of composite functions or multi-step process useful in subsequent analysis. The basis for the values in Tables 3.3 and 3.4 are provided in the Appendix.

3.4.1 Operating Modes and Load Profiles

The operating modes and temporal relationship between the microgrid generation and load determine the energy flow through the power conversion devices in the architectures of Fig. 2.1. The assumptions made regarding these modes and profiles were given in Sec. 2.4. *However, these are crucial to the estimation of system energy efficiency and are repeated here.*

The total power lost in the conversions depends on the energy[2] that passes through the different devices which in turn depends on the relative timing of the

analysis to higher efficiency, however, the *differences* in the efficiency curves between the power electronic conversion devices are what will bias the results toward AC or DC architectures. To fully account for these effects, a more detailed follow-on study is recommended.

[2]The efficiency of the power conversions depends on the fractional loading of the devices. This effect has been accounted for in detailed simulation and analysis of AC and DC architectures [7]. This study considers a simplified setting where the power conversion devices are always operating near to their peak efficiency so that the total losses can be based only on energy exchanges.

Composite function or multi-step process	Symbol	Value
AC bus to 50% high voltage DC loads and 50% low voltage DC loads	$e_{al,AC} = (e_{AC-AC} \times e_{sl,AC} + e_{AC-DC})/2$	0.950
DC bus to 50% high voltage DC loads and 50% low voltage DC loads	$e_{al,DC} = (e_{sl,DC} + 1)/2$	0.980
AC bus to battery to AC bus OR PV to battery to AC bus	$e_{brt,AC}$	0.905
DC bus to battery to DC bus OR PV to battery to DC bus	$e_{brt,DC}$	0.905

Table 3.4: Representative conversion efficiencies for composite functions or multi-step processes used in the architectures of Fig. 2.1 and based on the device peak load efficiencies in Table 3.3. Justification of these efficiencies is provided the Appendix.

microgrid generation and load [7]. Two extreme "corner cases" are considered here: 1) perfectly *matched* generation and load profiles and 2) generation and load profiles that are completely *disjoint*. Load and generation profiles that fall between these two extremes can be analyzed by taking linear combinations of these two results. Recall that we assumed that the PV generation, when present, is sized to supply the daily energy needs of the microgrid loads.

Battery operation has significant impacts on energy efficiency and should be optimized to best meet the microgrid owner's performance objectives. Here, we assume a relative extreme for battery operation, i.e., the battery is used to eliminate the swings in the net import/export of power caused by disjoint generation and load profiles. Recall that the battery is sized to store enough energy to supply the daily energy needs of the microgrid loads.[3]

3.4.2 Analysis

To enable this analysis to be modified for different assumptions regarding device efficiency, Table 3.5 displays the results as a function of individual device efficiencies and provides the numerical results for the device efficiencies given in Tables 3.3 and 3.4. Below, we provide a discussion of a few of the cases.

[3]A more rigorous analysis should be done using realistic generation and load profiles and part-load efficiencies using an optimal dispatch tool like DER-CAM[28]. This is recommended as part of a follow-on study.

Architecture	Load	Efficiency	Value
a) AC network	M	$e_{DC-AC}e_{al,AC}$	0.927
···	D	$e_{DC-AC}e_{al,AC}$	0.927
b) DC network	M	$e_{DC-DC}e_{al,DC}$	0.956
···	D	$e_{DC-DC}e_{DC-AC}e_{AC-DC}e_{al,DC}$	0.901
c) AC μgrid, PV, Battery	M	$e_{DC-AC}e_{al,AC}$	0.927
···	D	$e_{brt,AC}e_{al,AC}$	0.860
d) DC μgrid, PV, Battery	M	$e_{DC-DC}e_{al,DC}$	0.956
···	D	$e_{brt,DC}e_{al,DC}$	0.887
e) AC μgrid, firm generation	M	$e_{al,AC}$	0.950
f) DC μgrid, firm generation	M	$e_{AC-DC}e_{al,DC}$	0.946

Table 3.5: Energy efficiencies of the six reference architectures in Fig. 2.1. For each architecture, two load and generation profiles are considered—M=Matched with perfectly overlapping generation and load and D=Disjoint with no overlap of generation and load. For architectures with PV and a battery (c and d), the battery is used to eliminate the export flows to the main AC grid so that the power electronics interface can be made unidirectional for the DC microgrid.

AC Network In an AC network, the AC grid acts like a 100% efficient storage system, and the timing of the PV generation relative to the load does not matter. In either the Matched or Disjoint case, the composite efficiency is the product of the efficiency of delivering power from the PV's DC bus to the AC bus times the efficiency of delivering power from the AC bus to the aggregate DC internal loads, i.e. $e_{DC-AC}e_{al,AC}$ = 0.976 X 0.950 = 0.927.

DC Network In the DC network, the bidirectional inverter/converter imposes a round trip efficiency for exchanges with the AC grid equal to $e_{DC-AC}e_{AC-DC}$ = 0.976 X 0.965 = 0.942. For the Matched case, this round trip exchange is avoided, and composite efficiency is the product of the efficiency of delivering power from the PV's DC bus to the main DC bus times the efficiency of delivering power from the main DC bus to the aggregate native DC loads, i.e. $e_{DC-DC}e_{al,DC}$ = 0.976 X 0.980 = 0.956. Avoiding the extra power conversion for the high-voltage, native-DC loads improves the overall efficiency. For the Disjoint case, the energy makes a round trip through the bidirectional inverter/converter lowering the efficiency to $e_{DC-DC}e_{al,DC}$ X $e_{DC-AC}e_{AC-DC}$ = 0.956 X 0.942 = 0.901.

Comparison of AC and DC Networks For this study, a Network is a power system that is not managed in any way to improve its economic or technical performance. Therefore, whether the load and generation are matched or disjoint is dependent on the existing load profiles rather than, e.g., active load management. If the load and generation are not well matched, a DC network will have an efficiency that is $\sim$ 2-3% lower than a comparable AC network. On the other hand, if the load and generation profiles happen to be matched, then the DC network enjoys a $\sim$ 2-3% efficiency advantage.

AC Microgrid + PV + Battery When generation and load are already Matched and there is no reason to charge or discharge the battery, the energy flows are the same as in the AC network, and the efficiencies are also the same, i.e. $e_{DC-AC}e_{al,AC}$ = 0.976 X 0.950 = 0.927. In the Disjoint case, the battery must absorb all of the energy from the PV system and then deliver that energy to the aggregate DC-internal loads at a later time. The efficiency of this two-step process is $e_{brt,AC}e_{al,AC}$ = 0.905 X 0.950 = 0.860. As expected, the use of storage to manage the net flow of power leads to significant losses in the round trip through the battery.

DC Microgrid + PV + Battery With the same battery operating paradigm as for the AC microgrid, similar logic can be applied to determine the efficiencies of the DC microgrid. In the Matched case, the battery is not charged or discharged, and the operation and efficiencies are the same as the DC network under Matched load, i.e. $e_{DC-DC}e_{al,DC}$ = 0.976 X 0.980 = 0.956. In the Disjoint case, the battery must absorb all of the energy from the PV system and then deliver that energy to the aggregate DC internal loads at a later time. The efficiency of this two-step process is $e_{brt,DC}e_{al,DC}$ = 0.905 X 0.980 = 0.887. As expected, the use of storage to manage the net flow of power leads to significant losses in the round trip through the battery.

Comparison of AC and DC Microgrids With PV + Battery The addition of the battery enables the management of power flows and the elimination of power flows though the lossy power electronic interface between the DC microgrid and the main AC grid. With this management, the DC microgrid is able to retain its $\sim$ 2-3% efficiency advantage over the the AC microgrid for both Matched and Disjoint generation/load profiles. Although the DC microgrid architecture can perform better than the AC microgrid architecture, *both the AC and DC microgrid architectures perform significantly worse when the battery is used in day-to-day operations to manage power flows locally.*

AC Microgrid With Firm Generation The inclusion of firm generation complicates the analysis of the architecture efficiency because the efficiency of the generator can depend strongly on loading and speed. In fact, at least one manufacturer uses an AC-to-DC-to-AC converter to allow more flexible prime mover operation to reduce the emissions below regulatory levels [29]. In this generation unit, the prime mover's energy efficiency is also improved which helps to offset some of the losses incurred in the multiple power conversion steps. Here, we will neglect these issues, assume the generator is run to cover microgrid loads, and focus on the power conversion steps themselves. In the AC architecture, the electrical losses are from the conversion of power from the AC bus to the DC internal loads, i.e. $e_{al,AC}$ = 0.950.

DC Microgrid With Firm Generation Similar logic applies to the DC architecture, but the power from the generator passes through an AC-DC conversion step to get to the DC bus, but can then be used directly by the 50% of the native DC loads at high voltage, i.e. $e_{AC-DC}e_{al,DC}$ = 0.965 X 0.980 = 0.946.

Comparison of AC and DC Microgrids With Firm Generation Although there is a difference in efficiency of these two architectures, the uncertainty surrounding the effect of the architecture on prime mover efficiency is too large to draw any firm conclusions.

3.5 Operating Costs

A microgrid can reduce its net operating costs in three ways: 1) improvements in energy efficiency reduces net energy imports, 2) the time of energy imports can be modified to reduce costs against a time-of-use tariff, demand charge, or other time-dependent energy billing, and 3) the microgrid collects revenue by supplying ancillary services to the AC grid. With respect to supplying ancillary services, there is no fundamental difference between an AC and DC architecture. In the DC architecture, the ancillary services are supplied from a single power electronics interface, but just like and AC architecture, providing these services requires coordination of multiple assets inside the microgrid.

In the context of this idealized study of generic architectures, the two managed microgrid systems (whether AC or DC architectures) are using microgrid generation and storage to reduce power imports from the main AC grid to zero so that the microgrid's energy and demand charges are zero. Our assumptions do not allow the $\sim$ 2-3% energy efficiency advantage of DC architecture for PV+Battery accrue as reduced operating costs. Instead, they show up as reduced capital cost because fewer resources are need to offset the microgrid's load. In Sec. 3.3, we estimated the capital cost of the power electronics components in AC and DC architectures, but did not include the generation or battery resources. A total of 100 kW of PV generation at $\sim$\$4/W adds \$400,000 to the the capital cost in Sec. 3.3 for both AC and DC architectures. A 3% reduction in capital cost for the DC architecture corresponds to a savings of \$18,000. This difference could be significant enough to influence an investment decision, however, it seems relatively small compared to the larger difference in capital cost of power electronics devices driven by architectural considerations.

3.6 Engineering Costs

It is anticipated that microgrids will be installed in diverse environments that may require individualized design solutions. Assessing the costs associated with these details is beyond the scope of this generalized analysis, but it may be important for the specific applications in Section 5. Here, we seek to analyze two common functionalities and components—control systems and communication systems. The goal is not to design these systems, rather, this study seeks to distinguish between the properties of these systems for AC and DC architectures.

3.6.1 Communication Systems

Power Over Ethernet (PoE) [30], Universal Serial Bus (USB)[31], and Power Over HD Type-T (PoH) [32] have all combined communications with the distribution of DC power on the same set of wires at voltages up to $\sim$ 55 V DC and powers up to 100 W. The use of the same wires is perhaps not that advantageous—an additional set of wires could be added to AC wiring to enable communications in a similar fashion. However, the logical connection between the wires that are carrying the power and the power consuming device enables a mode of device discovery and power and voltage level negotiation [32]. This functionality could enable an automatically reconfigurable DC microgrid that approaches the plug-and-play capability of today's computers.

DC Architectures The implementation of these concepts in DC architectures is not straightforward. Today's power management capabilities of PoE, USB and PoH rely on a hub-and-spoke network architecture *with a single device at the end of each spoke.* Such an architecture may not be limiting for the low-voltage (24-48 V DC) loads where cable lengths are limited by Ohmic losses. However, the high-voltage networks will certainly incorporate many devices on a single run of cable. The communication protocols used in PoE, USB, and PoH are not applicable in this architecture. Plug-and-play DC architectures would require the development of new protocols that enable device identification and packet routing in this more complex network architecture.

AC Architectures If plug-and-play and automated configuration is a highly desirable functionality, it could also be built into an AC architecture. For example, a separate set of wires or fiber optic cable could be built directly into normal AC power cabling. Such an approach would suffer from the same difficulty associated with multiple devices on a single cable run, but in a hub-and-spoke network, the identification procedures could operate in a similar fashion. The lower voltage DC circuits would ease safety considerations, however, the 380 V DC would present the same safety issues as an AC system.

Summary Because of restrictions on network architecture, the combined communications and power capability of PoE, USB, and PoH are not directly transferable to high power DC microgrid architectures where high voltage ($\sim$380 V DC) is needed. If desired, similar communication capabilities can be built into the physical layer in AC microgrid architectures. For this high-level analysis, DC architectures do not appear to provide a major advantage over AC architectures for microgrids with a rating of larger than 100 kW.

3.6.2 Control Systems

Although DC microgrids do not have a power system frequency, their control systems can be analyzed in a framework similar to AC microgrids and power systems. Specifically, the control is separated into two time scales—a fast time scale on the order of milliseconds to a few seconds or even a minute and a slower ($\sim$ minutes) time scale. In analogy with AC power systems, we call control at the fast time scale "primary" and the slower time scale "secondary".

The "secondary" controls generally use relatively slow communications to manage generator, storage, and load power for economic considerations and voltage set points for loss minimization. Other slow functions can also be managed at the secondary control time scale, e.g. (potentially adaptive) protection settings or device status. *The implementation of the secondary control is not anticipated to be significantly different in the AC or DC architectures.* In contrast, the primary control responds to fast microgrid transients or other upsets. The required speed of the primary response and critical nature of the control makes a communication-based control perhaps less reliable. Below, we discuss the primary control in a communication-free setting.

AC Architectures AC architectures are able to use frequency to communicate the system-wide imbalance of real power. After transients settle, the *steady-state* frequency is uniform throughout the microgid which enables well-controlled sharing of load deviations among the microgrid generation sources (or storage), e.g. by frequency droop control [33]. In addition, certain implementations [33] of this form of control does not require the communication of microgrid state, i.e. islanded or grid-connected. These advantages are somewhat tempered by the complexity of controlling and stabilizing *transients* in mixed microgrids, i.e. microgrids with both rotating generation and inverter-based generation (this architecture is not shown directly in Fig. 2.1, but would be a combination of Fig. 2.1c and e). In these mixed systems, the components may have very different response speeds creating very different transient dynamics depending on the location of a fault or other disturbance. These non-uniform device responses complicate the design of control and protection systems in mixed microgrids. AC-DC-AC power electronic interfaces have been developed to simplify the integration of rotating generation with inverter-based generation [29], but this begins to look much like a DC architecture raising the possibility that a DC architecture would be more advantageous.

DC Architectures In a DC architecture, voltage replaces frequency as the physical variable that can be used to communicate the imbalance of generation and load at the "primary" control time scale [34]. As opposed to frequency in AC architectures, voltage in DC architectures is a "local" variable, i.e. the droop of voltage depends on the location of the change in load relative to the location of generation and the measurement point. When using voltage as the indicator of generation-load imbalance, the response of the generation or storage sources will not be uniform across DC microgrids. Although the configuration of the response at the primary time scale may not be desirable, but it can be adjusted at a slower time scale using the secondary control. However, at the faster primary time scale, the response is coming entirely from power electronic devices with more or less equivalent dynamics avoiding the complications of controlling mixed microgrids in AC architectures.

Summary The power electronic components in DC microgrids can be designed to have fast and relatively uniform *transient* responses. In contrast, the natural transient response of large rotating machines is slower than power electronic devices and cannot be easily modified by design. The uniformity of the transient response in DC architectures potentially makes them less sensitive to the location of faults and other disturbances, which may lead to control and protection system designs that are less sensitive to the details of the microgrid design and more universal (and less expensive) than for AC architectures.

3.7 Environmental Impact

The extended discussion of energy efficiency will now pay dividends in the assessment of environmental impact, discussed here in terms of CO_2 emissions. Repeating the overall conclusion from the energy efficiency discussion–when AC and DC systems are compared for similar architectures and for similar operating

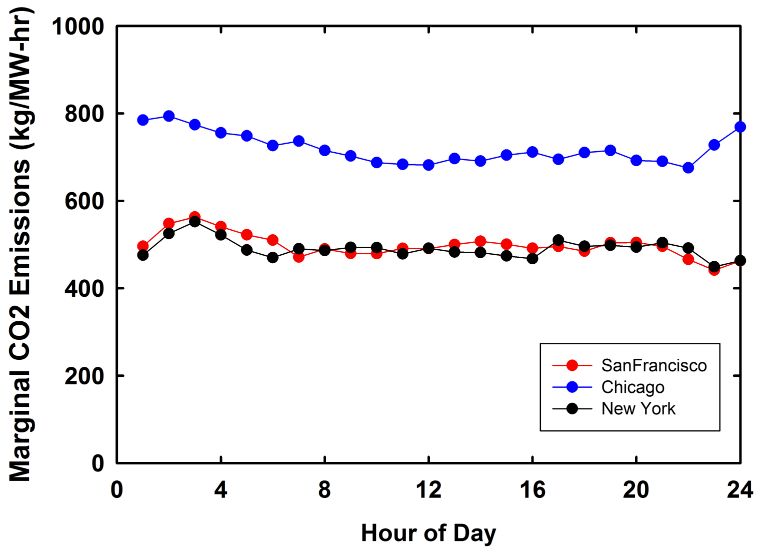

Figure 3.1: Marginal CO_2 emissions for three representative US cities [35].

paradigms, the energy efficiency differences are $\sim$ 2%. This difference corresponds to approximately 17,520 kW-hrs/year for a 100 kW system continually operating at full capacity. If this difference in energy were supplied by fossil-fired generation, the CO_2 emissions can be estimated from the marginal CO_2 emissions rates[35] in Fig. 3.1. A typical rate is $\sim$ 500-800 kg/MW-hr and is approximately uniform through the day. At the higher marginal emissions rate, the 2% improvement in energy efficiency corresponds to an annual reduction of $\sim$ 14 metric tons. Even if the CO_2 is priced at \$50/metric ton, the reduction is only equivalent to \$700/year—a cost differential that is not large enough to influence the decision between AC and DC architectures.

3.8 Power Quality

The analysis of the power quality metric follows the categories and definitions of power quality provided by EPRI in [36]. The “Customer Service” category in [36] is beyond the scope of this study. The “Continuity of Supply” category has been partially addressed in the Secs. 3.2 and 3.6.2 . Our primary concern for the power quality metric is the “Voltage Quality” category in [36]. Within the Voltage Quality category, EPRI breaks down power quality into several subcategories that are primarily aligned with the time scale of the disturbance. However, the microgrid architectures in Fig. 2.1 allow a natural separation of the analysis into disturbances that originate from outside of the microgrid (external) and those that originate inside (internal):

External disturbance For external disturbances that originate in the main AC grid, the DC architectures in Fig. 2.1 have significant advantages. A fast responding power electronics interface between the AC and DC systems (and potential storage on the DC bus) will provide a buffer from nearly all of the Voltage Quality subcategories in [36]. One exception is the very fast disturbances in the "Transients" subcategory. Here, the speed or spectral content of the disturbance may approach or exceed the switching frequency of the power electronics interface allowing the disturbance to effect the voltage on the DC side of the interface. However, the disturbances in the other subcategories are generally slower than typical switching frequencies and will be effectively filtered out by the interface power electronics.

In contrast, AC architectures are directly connected to the main AC grid with a Thevinin equivalent impedance that is typically quite low. This limits the ability of reactive power sources inside the AC microgrid to mitigate a short-term and long-term voltage sag or swell or voltage flicker. Therefore, when subject to an external disturbance, often the only option to improve the power quality inside the AC microgrid is to island the system—an operation that always involves some risk. For a power quality issue that appears suddenly (e.g. a voltage sag due to a nearby fault), an AC microgrid will suffer reduced power quality until the switch at the PCC is able to open and island the microgrid, e.g. up to 6-10 AC cycles for an electromechanical switch. The interface power electronics in the DC microgrid will respond significantly faster and limit the exposure to reduced power quality.

Internal disturbance For internal disturbances, the distinction between AC and DC architectures is less clear. Fore the more continuous disturbances such as flicker and waveform distortion, the likely causes are the power electronics that comprise the microgrid. The origin and mitigation of these disturbances is outside the scope of this study. The shorter-term power quality issues (primarily voltage sag) are likely due to faults or other transients (e.g. motor starts) inside the microgrid. For faults, the primary mode of mitigation is to isolate and clear the fault. The longer the time delay for fault identification and protection coordination, the greater the impact of the voltage sag. In the DC architectures, the buffer provided by the AC-DC power electronics interface provides a clean separation between external and internal faults potentially leading to faster fault identification and clearing and smaller transients.

Summary Overall, the DC architectures have a clear qualitative advantage over AC architectures for power quality issues that originate from outside the microgrid. DC microgrids have the potential to reduce the duration of transients and improve power quality for faults inside the microgrid.

3.9 Resilience

Assuming a similar set of energy assets, there is little if any difference in the ability of the power systems to serve loads during extended outages. Therefore, for the purposes of this study, *the "Resilience" metric from Section 2.2 will not play a major role in judging the applications in Section 5*, unless an unusual system configuration arises.

3.10 Summary Metrics Analysis and Recommendations

Table 3.6 is a summary of the analysis of the metrics from Section 2.2 based on the information available during this study and the assumptions made about microgrid architecture and energy asset sizing in Fig. 2.1. Based on this summary, we recommend two DC microgrid applications for further detailed simulation study to better identify the benefits and drawbacks of DC versus AC architectures. The first study focuses on the steady-state integration of DC-based microgrid sources and the potential impact on capital cost and economic efficiency. The second study focuses on the possibility of simplified primary control systems for DC microgrids and the potential impact on post-disturbance transient dynamics and the ability of DC architectures to operate through major disturbances:

1. **DC Microgrid as an Efficient, Low-Cost Platform for Economic (Steady-State) Integration—**(This application is related to the PV+Battery microgrids in Fig. 2.1 c) and d).) Many new distributed energy resources are direct DC, e.g. PV generation, stationary batteries, mobile batteries, and

Metric	Rank	DC Relative to AC Architectures
Safety and protection	0	Both AC and DC have adequate protection devices
Reliability	0	Assuming power electronics at AC/DC interface are sized appropriately to account for potential failures (see Fig. 2.1
Capital cost	+/-	DC architecture for a **PV+Battery microgrid enjoys** $\sim$**\$1/W lower cost** for power electronics if the energy assets are sized so that power export is not required while N-1 reliability is maintained. However, DC architectures for the two other cases **(PV Network and Firm Generation) have** $\sim$**\$0.60/W higher cost** for power electronics under similar reliability and sizing assumptions
Energy efficiency	+	The DC microgrid architectures enjoy a 2-3% efficiency increase over AC architectures assuming that the microgrid energy assets are sized so that power export is not required.
Operating cost	0	Under the assumption of the study, energy efficiency improvements count toward reductions in capital cost.
Engineering cost	+	Primary (distributed) control systems for DC architectures are potentially more universal, which may lower engineering costs
Environmental impact	0	Under the assumption of the study, energy efficiency improvements count toward reductions in capital cost, not towards less fossil-generated electricity purchased. If efficiency improvements were credited to lower marginal CO_2 emissions reductions, the monetary value is not large.
Power quality	+	Power electronics at the AC/DC interface provides buffer against external disturbances
Resilience	0	Similar properties

Table 3.6: Summary of the metrics from Section 2.2 for AC and DC architectures. + (-) indicates an advantage (disadvantage) for the DC architecture over its related AC architecture. 0 indicates no perceived advantage for either architecture. Multiple rankings are given if there are differences between the microgrid configuration in Fig. 2.1.

fuel cells. Also, many high efficiency loads are also direct DC [4]. A microgrid utilizing a DC bus may avoid many of the power conversion steps required when using an AC bus, potentially leading to higher energy efficiency and improved economic operation for DC microgrids. However, these benefits need to be carefully weighed against the potentially higher cost of interfacing a DC microgrid to the bulk AC power systems. To provide more accurate estimates of these costs and benefits, this scoping study recommends a more detailed simulation-based study of comparable AC and DC microgrids that, at a minimum, accounts for the following factors:

(a) realistic microgrid load and generation profiles (daily and annual)

(b) the use of realistic AC-DC, DC-AC, and DC-DC power conversion efficiency curves that account for the typical decrease in efficiency at part load

(c) fair and detailed treatment of the conductor losses in AC and DC microgrids including the effects reactive power flow and mitigation of losses through additional capital expenditures on conductors.

(d) sensitivity of the reliability of DC microgrids (i.e. the ability to deliver power to the microgrid loads) to the sizing of the power electronics at the AC-DC interface to the bulk power system and the sizing of microgrid's distributed energy resources.

(e) at equivalent reliability, the sensitivity of the economic performance of DC microgrids to the sizing and capital cost of the microgrid energy resources and power electronics at the AC-DC interface to the bulk power system, including the impact of this sizing on the ability of the DC microgrid to export power to the bulk AC system

We emphasize that all of the assessments and effect mentioned above should be done using realistic load and generation profiles, not peaks or averages. The main objective of the recommended study is to provide accurate estimates of the economic performance of AC and DC microgrids for designs that yield equivalent reliability, where reliability is considered in the N-1 sense of being able to serve all critical load after the loss of any one component.

2. **High Survivability DC Microgrids—**(This application is related to any of the microgrids in Fig. 2.1.) Microgrids are subject to many different

types of internal and external disturbances. To be ”survivable”, the post-disturbance microgrid dynamics should converge to steady-state operation with no loss of critical load and minimal loss of non-critical load. The sources in a DC microgrid only have to reach a steady state DC voltage whereas an AC microgrid's sources must achieve a steady state voltage magnitude and frequency. The power electronics at the AC-DC interface may shield DC microgrid dynamics from many external disturbances leading to higher survivability. For internal disturbances, the fewer dynamical states of the DC microgrid may lead to simpler controls, may make achieving the new steady state easier and potentially lead to improved survivability. A greater immunity to external and internal disturbances could lead to higher reliability and lower engineering costs. To provide a better estimate of these potential survivability benefits, this scoping study recommends a more detailed simulation-based study of comparable AC and DC microgrids that, at a minimum, accounts for the following factors:

(a) for the AC and DC systems, equivalent bus, line, and source architectures that include at least two buses with a mix of sources at each bus, e.g. two DC direct sources (e.g. one PV generators and one battery) or one DC direct source and one AC native source (e.g. a natural gas-fired rotating machine). These sources should be interfaced to the microgrid bus as appropriate for type of system under consideration.

(b) realistic and comparable tripping conditions for both the DC-direct and AC-native generation sources

(c) potential differences between unipolar and bipolar DC microgrid configurations

(d) equivalent internal and external disturbances that include a range of extreme but plausible cases, including:

    i. outage of the AC grid at the substation supplying the microgrid with subsequent (delayed) microgrid islanding

    ii. fault on the AC grid near the interface to the microgrid with subsequent (delayed) microgrid islanding

    iii. faults on the microgrid buses that are cleared with and without isolating the the faulted bus

    iv. large changes in microgrid load while grid connected and islanded with large changes in motor load likely being the most severe.

> The performance of the AC and DC microgrids should primarily be judged on their ability to maintain service to critical loads following the disturbance with a secondary consideration of the cost of the control system, generation sources, and power electronics. The survivability study may want to consider using the same microgrid architectures as in the "Low-Cost Platform" study for comparison.

This study also suggests potentially revisiting a third application in the future. A trigger for revisiting this application is further increases in device power level on PoE or PoH networks:

Low Power Network with Differentiated and Automatically Evolvable Power Quality and Reliability—(This application is related to the DC network in Fig. 2.1 b) or the microgrid in Fig. 2.1 d).) These networks and microgrid are generally low voltage PoE systems where communications and power distribution are naturally integrated into the same wiring and switching. The integrated architecture and communications protocol naturally enables end device self identification with the potential for automated network or microgrid reconfiguration. At current device power levels, it is not clear if these networks will ever achieve the minimum power threshold used in this study and become large enough to be relevant to DOE Office of Electricity. However, the rapid evolution in this area justifies continued monitoring of this technology.

4. Appendix A—Voltage-Conversion and Battery Efficiency Assumptions

At high enough power and high enough voltages, voltage-to-voltage conversions are routinely accomplished with energy efficiency $e > 0.95$. AC-DC and DC-AC conversions tend to be slightly less efficient than purely DC-DC conversions. Here, we cite references that document efficiencies we consider to be commercially available and/or reasonable in 2014.

- Photovoltaic Maximum Power Point Trackers (MPPTs) are as high as 99.9% efficient [23]. We ignore MPPT losses and treat them as being essentially 100% efficient and part of the photovoltaic strings themselves.

- Based on Refs. [23, 24] for commercially available photovoltaic inverters, we take $e_{DC-AC} = 0.976$.

- High-voltage DC buses are still a novelty, with high-power, high-voltage DC-DC converters being rare. For converting photovoltaic power to 380 V DC, Ref. [25] documents an efficiency of 96%. However, this value would be too conservative, because it is based on conversion to a low voltage, and other indications are that DC-DC conversions are more efficient than DC-AC conversions at high voltage. We expect that $e_{DC-DC} \geq e_{DC-AC}$ if and when photovoltaic DC-DC converters become widespread. Thus, we take $e_{DC-DC} = 0.976$ for the present study.

- Converting high-voltage DC to low-voltage DC (e.g., 380 V to 12 V) is less efficient than converting to high-voltage DC to high-voltage DC. Based on Ref. [25], we take $e_{sl,DC} = 0.96$ and $e_{sl,AC} = 0.95$ for low-voltage, "small" DC loads.

- Converting AC grid power to 54 V DC at kW powers is routine at 96.5% efficiency [26, 27]. Thus, we assume $e_{bl,AC} = e_{AC-DC} = 0.965$ for "big" loads.

- We assume that half of the total system power is consumed by small loads and half by big loads. For an AC-grid bus, the average conversion efficiency supplying power to the loads is then $(e_{bl,AC} + e_{sl,AC})/2 = 0.958$. For a DC-bus, the big loads are driven directly from the 380 V DC, so the average conversion efficiency supplying power to loads is $(1 + e_{sl,DC})/2 = 0.980$.

- The lithium-ion battery literature [37] specifies an electrochemical round-trip efficiency of over 95% for large lithium-ion batteries, not including power converters. (For sealed lead-acid batteries, this would be closer to 90%.) For connection to AC, we also account for high voltage AC-DC and DC-AC conversions as the battery is charged and discharged, using the high-power, high-voltage conversion efficiencies discussed above, obtaining $e_{brt,AC} = 0.976 \times 0.95 \times 0.976 = 0.905$ for the round-trip DC-to-AC storage in lithium-ion batteries. This is consistent with [38]. Similarly, for use in a DC microgrid, we estimate $e_{brt,DC} = 0.976 \times 0.95 \times 0.976 = 0.905$ for the round-trip DC-to-DC storage in lithium-ion batteries.

- Slightly higher AC-DC voltage-conversion efficiencies seem likely in the future [39, 40].

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5. Appendix B—DC Microgrid Applications

Below, we present a summary of the available analysis for the DC microgrid applications suggested by the members of the study team. Each of these analyses is a self-contained document with its own bibliography and caption numbering.

Application #1—DC Microgrid as an Efficient, Low-Cost Platform for Economic (Steady-State) Integration

This application compares a benchmark AC microgrid with its counterpart in DC having two objectives. First, we examine the electric power losses of each microgrid. These occur because of (a) the distribution of electric power, i.e. AC line losses vs. DC line losses, and (b) the efficiency of the converters, i.e. AC/DC/AC converter efficiency vs. DC/DC converter efficiency. Second, we compare the equipment costs that are necessary for an AC vs. a DC microgrid.

In order to carry out the comparison, we needed a benchmark microgrid model. As there is significantly more research carried out in AC microgrids, we looked for a benchmark AC microgrid, which we could then convert to an equivalent DC microgrid, with the same active power consumption and generation, and study the difference between AC and DC technology.

We could find no available benchmark AC microgrid system in 60 Hz, so we used the microgrid system presented in Figure 1 to carry out our comparisons [1]. This assumes 50 Hz system frequency and 400 V as the AC distribution voltage. Taking into account that in the US the standard residential voltage is 120 V, we would probably expect higher losses in a microgrid designed for the US system. A minor role in the increased losses will also be due to the increased frequency (higher angular frequency ω and thus higher reactance for the inductances).

Conversion Losses

There are several different converters in the market. Usually DC/DC converters are somewhat more efficient than AC/DC. In order to account for the best possible case for AC, we assumed that both AC/DC and DC/DC converters have 97% efficiency. (Note: in a discussion with Prof. J. Kolar from ETH Zurich, he mentioned that current state-of-the-art *transformerless* AC/DC converters have efficiencies similar to state-of-the-art DC/DC converters of about 97%. AC/DC converters including transformers – galvanic isolation is necessary for several home appliances – have lower efficiencies). As a result the difference in the conversion losses we will see in this study is only dependent on the actual amount of energy that flows through the converter.

Description of the AC microgrid

The benchmark AC microgrid consists of a 400 V low voltage radial feeder, which is connected over a transformer to the 20 kV medium voltage network [1]. It consists of AC loads, the main grid in-feed, and distributed generation (DG). The generating sources are a 30 kW battery storage, a 30 kW gas microturbine, a 10 kW fuel cell, a 10 kW wind turbine, and two solar photovoltaic (PV) systems of 10 kW and 3kW respectively. Both solar PVs are connected to a single phase, while all other generation is connected to all three phases.

Using standardized load coincidence factors, the maximum load demand of the feeder is about 100 kW, consisting of AC residential loads some of them connected to a single phase, and the rest being three phase loads. The power factor for all loads is assumed 0.85 lagging, leading to an apparent power demand of 116.4 kVA.

The distance between two poles (illustrated by thick dots in Figure 2) is 35 m, while each service cable has a length of 30 m. As a result the total feeder length is about 300 m.

The benchmark AC microgrid model contains also several additional details about grounding, hourly load profiles and the details of each cable.

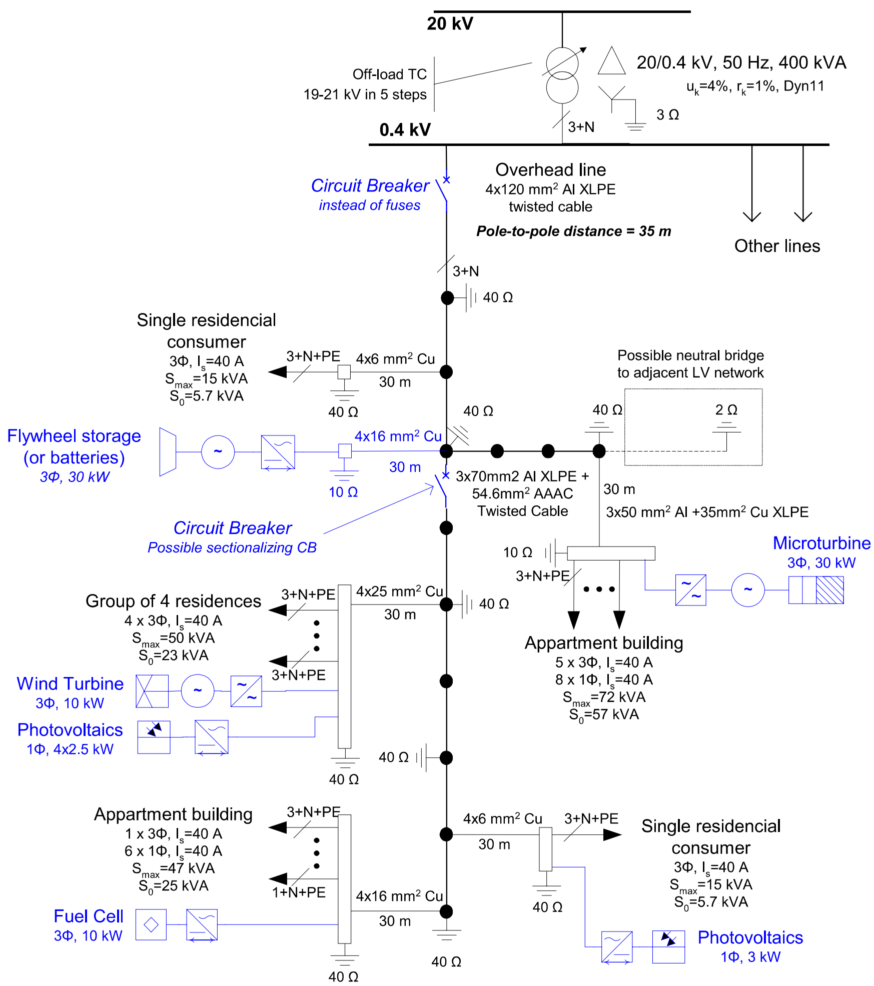

Figure 1: Benchmark AC microgrid system [1]

Description of the DC microgrid

The DC microgrid we created for this study has almost exactly the same single-line diagram as its AC microgrid counterpart. The main difference is that instead of 20/0.4 kV transformer, we placed an AC/DC PWM converter, which supplies the DC feeder with 380 Vdc.

All loads in the DC microgrid have been assumed DC loads, consuming exactly the same active power as in the AC microgrid (reactive power is obviously non-existent in a DC environment). In our studies later in this section, we carry out sensitivity analyses, assuming different ratios of AC vs. DC loads in both the AC and DC microgrid.

The DG provides exactly the same active power. The difference is that instead of having a DC/AC converter for the battery, the fuel cells, and the solar PV, we now have a DC/DC converter. Additionally, instead of having both AC/DC and DC/AC converters for the microturbine and the wind turbine, in the DC microgrid we have a single AC/DC converter.

Figure 2 shows the AC and DC microgrid we implemented in Digsilent Powerfactory [2] for our studies.

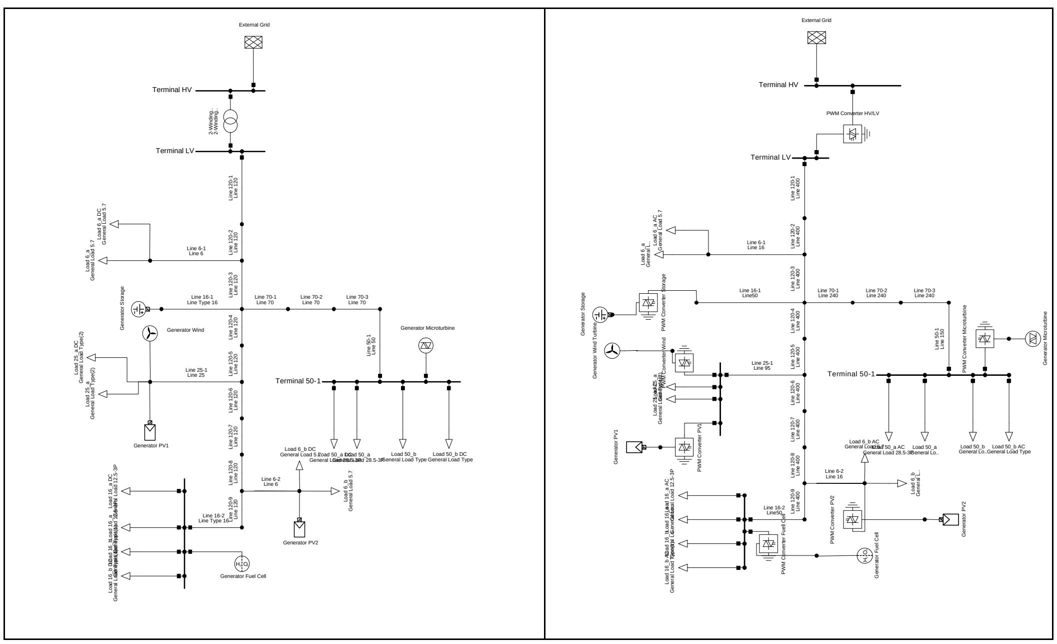

Figure 2: AC microgrid (left) and DC microgrid (right) implementation in Powerfactory

The AC microgrid consists of three phases and a neutral, while the DC microgrid has only one phase and a neutral. Therefore, the cables in the DC system have 1.83 times higher ampacity than their counterparts in the AC microgrid. For such a voltage and ampacity we found that the resistance of such a cable is 0.0778 per km. Later in this study we also theoretically investigate the option where we have two cables +/-190 Vdc instead of a +380 Vdc and a neutral.

Case Studies

As mentioned above, our comparison had two objectives: compare the electric power losses and compare the equipment costs occurring in an AC vs. a DC microgrid.

Our performance criteria are:

- network losses, and
- the amount of power that needs to be absorbed from the main grid.

We carried out in total four sensitivity analyses investigating the following:

a) different cable lengths,
b) load demand and the power factor of the loads,
c) the ratio between the main grid infeed and the local generation in the microgrid, and
d) the ratio between AC and DC loads

Main Grid Infeed

Papathanasiou et al. provides the kVA values of all loads and assumes a uniform power factor of 0.85 inductive. In this section, we also studied two additional cases, where the loads have the *same apparent power* but a power factor of 0.95 inductive and where the loads have the *same active power* but a power factor of 0.95 inductive. In the base case with a power factor of 0.85 inductive, the total apparent power of the load is 116.40 kVA and the total active power is 99.02 kW.

As a first step, we assumed that *all AC/DC, DC/AC and DC/DC converters are ideal and have no losses*. Our focus was to examine the difference in the grid infeed only because of the grid topology. In the next step we will include the converter losses.

Table 1 presents the results of our study.

		AC			DC	
		P [kW]	Q [kvar]	S [kVA]	P [kW]	Diff. (%)
cos(φ)=0.85	Grid Infeed	9.05	62.36	63.01	6.6	-90%
cos(φ)=0.95 constant kW	Grid Infeed	7.87	33.01	33.94	6.6	-81%
cos(φ)=0.95 constant kVA	Grid Infeed	19.96	36.98	42.02	18.51	-56%

Table 1: Grid infeed for an AC Microgrid and its DC counterpart. Two different load power factors were investigated.

As we can see from Table 1, for both load power factors, the DC microgrid requires a substantially smaller power infeed from the main grid.

In the base case of cosϕ=0.85, the AC Microgrid requires the injection of 63.01 kVA from the grid, while the DC microgrid requires only the 1/10 of it – about 6.6 kW. Although the sizing of the AC/DC converter should also take into account security of supply issues and the reliability of the micro-sources, still the DC microgrid needs only a smaller size AC/DC converter, as it does not consume any reactive power. This could also result in benefits with respect to the sizing and cost of the necessary breakers, transformers, and, in general, protection, control and metering equipment in the DC microgrid case.

Microgrid DG Power Supply and Demand Profile

In the rest of our studies, we used the 24-hour load profile of the microgrid, as given in [1]. For the power generation, no data were available. We assumed that all generating sources are producing at the maximum of their capacity, except for the solar PVs, for which we assumed a supply curve from 6am to 6pm, reaching a maximum of 13 kW, as shown in Figure 3.

In Fig. 4, we observe that the network losses of the DC microgrid are substantially less than in the AC microgrid (the DC losses are between *70% to 90% less* than the AC losses). It should be noted here that the losses in the AC case amount to about 3% – 6% of the total energy consumption. In the DC case the losses amount to about 0.4% – 2%. Concerning the active power infeed from the main grid, we see that this is the same for both the AC and the DC microgrid. This is expected as both microgrids have exactly the same active power supply and demand profile. The difference is the *additional reactive power* injection in the AC microgrid that is not shown in Fig. 4.

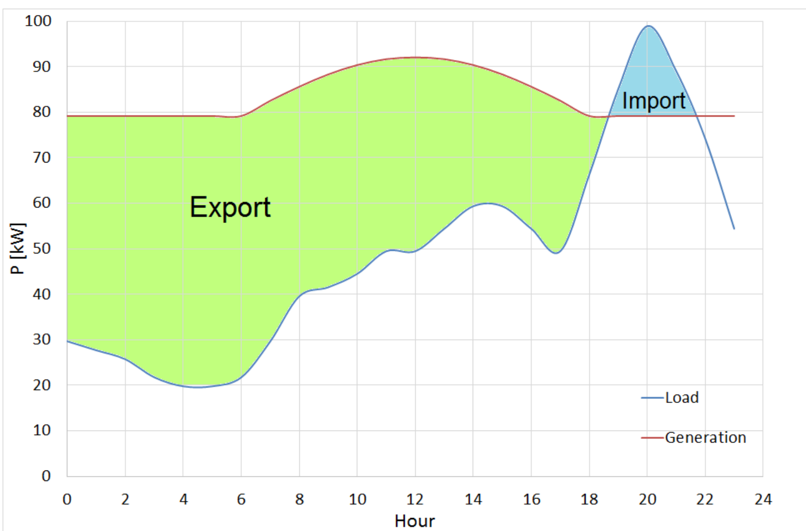

Figure 3: 24-hour Power Supply and Demand Profile of the Microgrid

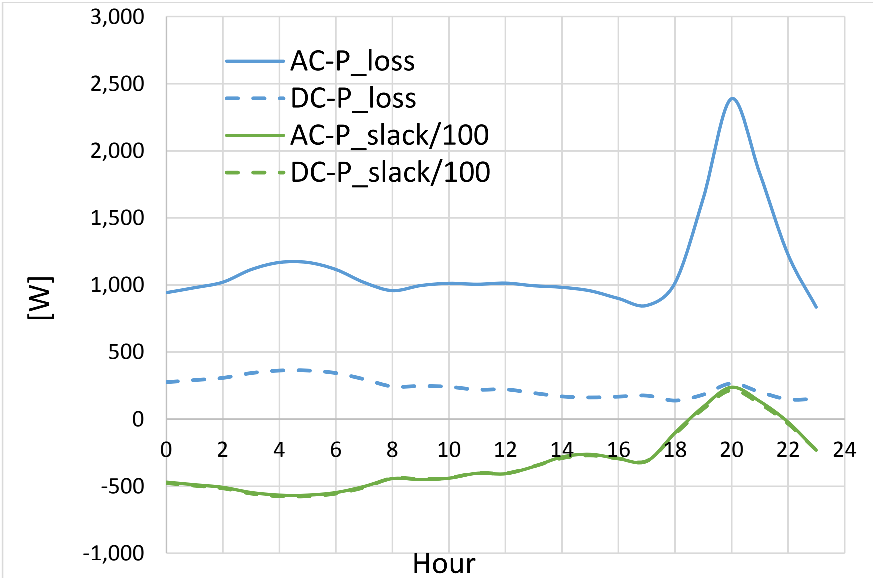

Figure 4: Network Losses (Blue lines) and *Active Power* Grid Infeed (Green Lines) of the AC vs. the DC Microgrid.

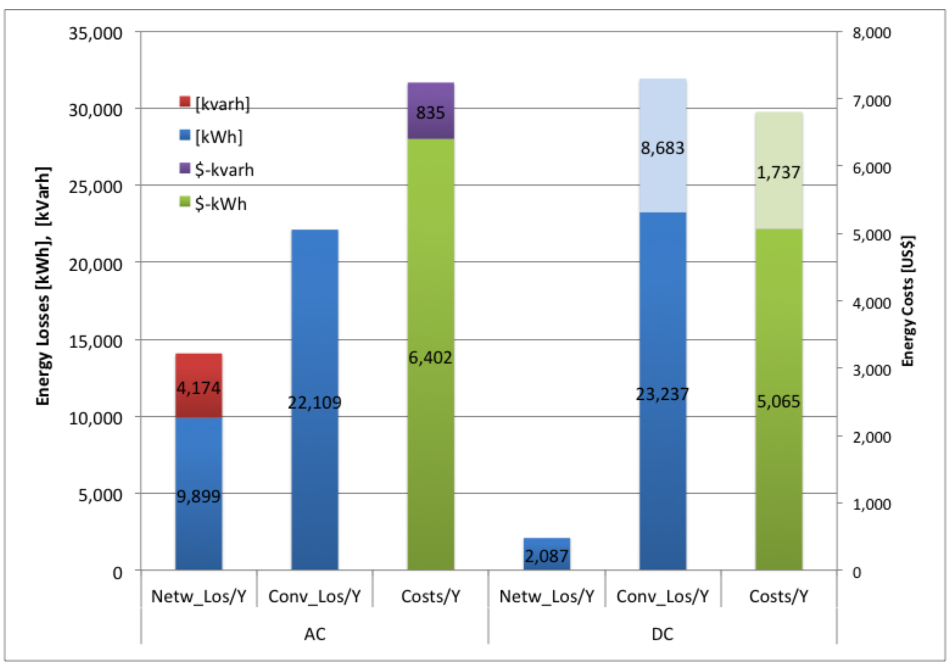

Figure 5: Energy Costs for Network and Converter Losses per Year. [losses are shown in blue/orange bars; costs are shown in green/purple bars; the light colors on the DC side correspond to the energy export-only through the main AC/DC converter]

Figure 5 shows the energy losses in kW and kVar extrapolated for a year, based on the 24-hour profile we simulated. We observe that the network losses are about *85% less* in the DC case. Considering the total converter losses, these are higher in the DC microgrid case, because of the extra AC/DC converter at the interface with the AC grid. As we can observe in Fig. 5, losses of about 8,683 kWh correspond to the main AC/DC converter losses due to the *export* of power to the AC grid. If the DC microgrid were equipped with a unidirectional (and not a bidirectional) inverter due to cost considerations, these converter losses would have been avoided. Due to the substantially less network losses in the DC microgrid, the energy costs *corresponding to the losses* are similar for both microgrids if we consider all converter losses. If we do not consider the losses of the main AC/DC converter *due to the power export*, then the costs are expected to be about 20% less for residential customers and about 30% less for industrial customers (charged also for reactive power). In this study the efficiencies for AC/DC and DC/DC converters were considered equal, which favors the AC case. If in reality the AC/DC efficiencies are lower than the DC/DC, the DC microgrid can lead to additional cost savings compared to AC.

Active Power Losses vs. Line-Kilometers

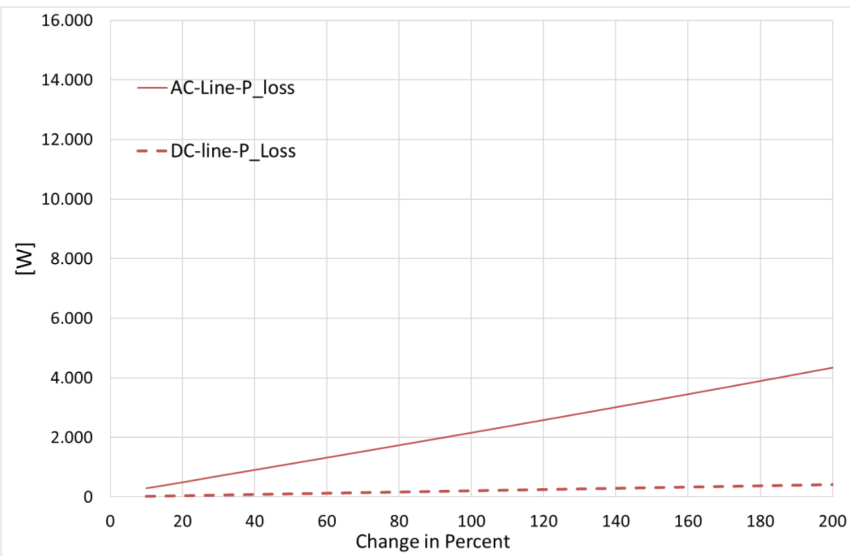

Figure 6: Change of Network Losses for increasing Cable Lengths

In this sensitivity analysis, we increased uniformly all cable lengths. At the 100% point, the cables have their nominal length as described in [1]. We vary the cable lengths from 10% to 200% of this length. We observe that the network losses at the AC grid are much more sensitive, i.e. increase more steeply as the cable length increases, than the DC network losses. This means that for microgrids covering larger areas, a DC microgrid will result in less losses and lower voltage drop.

Active Power Losses vs. Different Level of Load and Generation

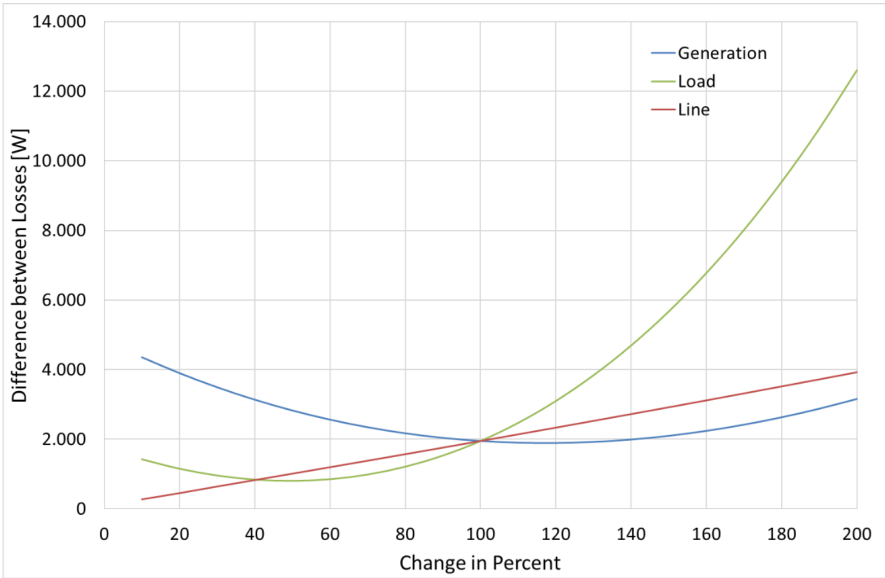

Figure 7: *Difference* in Losses between the AC and the DC microgrid

In Figure 7 we observe the *difference* between the network losses, as we vary the line length, the load demand, and the generation supply of the microgrid. Again, the 100% point reflects the nominal values as described in [1]. In all cases, the DC microgrid losses are lower than the AC network losses. So the difference represents how much higher are the AC network losses in comparison with the DC losses. We see that as the cable length increases, the difference between the AC and DC increases linearly. On the other hand, we observe an exponential increase of the network losses as the load demand increases. The difference between the AC and DC network losses has also a quadratic character with varying the ratio of the DG supply vs. the main grid infeed. For values close to 20% -- which means that the local DG produces only 20% of the initial values and the rest is supplied from the main grid -- the losses for both AC and the DC microgrid increase. This is due to the fact that a larger portion of the power supply is injected from the main grid. In case this power was produced locally by the DG, the transmission path to the loads would be shorter, which results in less network losses. In Fig. 7, we observe that with less amounts of electricity generated by the local DG, the difference between the AC and the DC network increases quadratically as well.

Network Losses for Different AC/DC Load Ratios and Power Factors

In this section, we investigate the effect of the load power factor and the ratio of AC over DC loads in the system. We vary two parameters: (a) the power factor: we assume that all loads consume the same amount of active power as in the nominal case; by varying the power factor, we vary the reactive power that is consumed, and as a result the total apparent power that should be supplied by the grid; (b) the AC/DC load ratio: with 100% we represent all loads as AC, while with 0% all loads are assumed as DC. As the power factor is only relevant for the AC system, we first focused on the AC microgrid. Figure 8 presents the network losses in the AC microgrid for different power factors and AC to DC load ratios. With 100% ratio no AC/DC converter is necessary. With an AC/DC ratio equal to 0%, all loads are assumed DC and have an AC/DC converter. If all loads are DC, the power factor is irrelevant and therefore no change is observed with respect to cosϕ. If we have a high amount of AC loads, we observe that the power factor plays a significant role. For the case of 100% AC loads, a cosϕ equal to 0.80 inductive results in network losses 6 times higher than a power factor equal to 1.

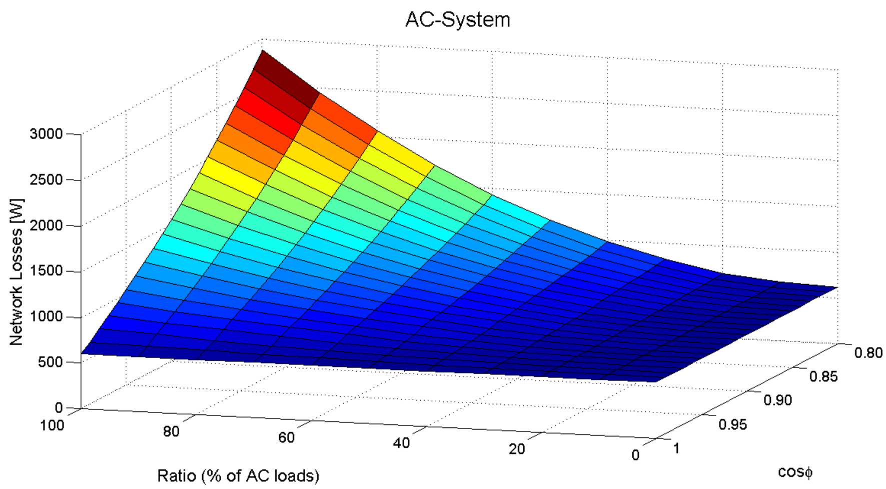

Figure 8: Network Losses in the AC Microgrid for different power factors and AC/DC Load ratios

Figure 9 presents the total losses in the AC microgrid system, i.e. network and converter losses. Here, the higher the amount of DC loads is, the more AC/DC converters we need, and therefore the total losses increase. We observe that for different power factors, there exist different optimal points. For example, in the ideal case where all loads have a power factor equal to 1, then optimally we would need only AC loads in the AC microgrid. In this way, we avoid all conversion losses from the AC/DC converters that are necessary for the DC loads. In a more realistic case of e.g. a power factor of 0.85, the optimal point would be an AC/DC load ratio of 30%, i.e. 30% AC loads and 70% DC loads. This is a trade-off between the network losses that increase the more AC loads with reactive power needs we have in the system, and the conversion losses that result from the AC/DC conversion. This trade-off is presented in Figure 10.

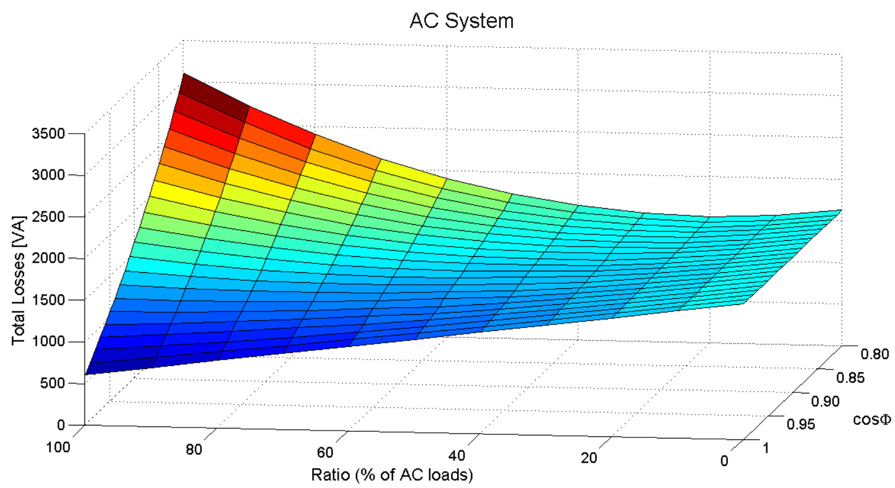

Figure 9: Total Losses (Network and Converter Losses) for different power factors and AC/DC load ratios

Besides the trade-off between network losses and conversion losses for the AC system, Figure 10 presents also the comparison between the total losses of the AC vs. the DC microgrid. We observe that irrespective of the AC/DC load ratio and the associated conversion losses, the DC microgrid results always to lower total losses than the AC counterpart.

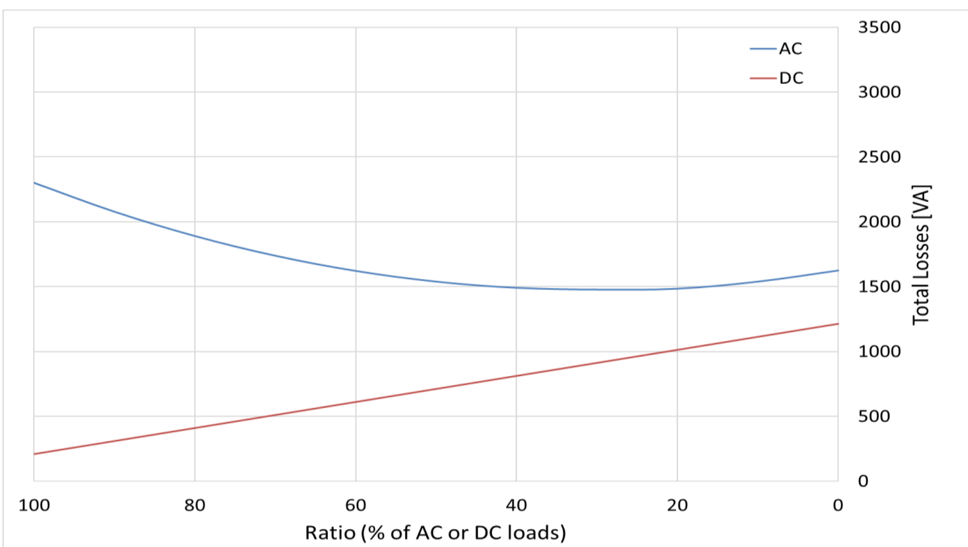

Figure 10: Comparison of the total losses between a DC and an AC microgrid for loads with power factor = 0.85 inductive. For the AC case, a ratio of 100% means that all loads are AC. For the DC case, a ratio of 100% means that all loads are DC.

Theoretical Investigation of Different DC Microgrid Topologies

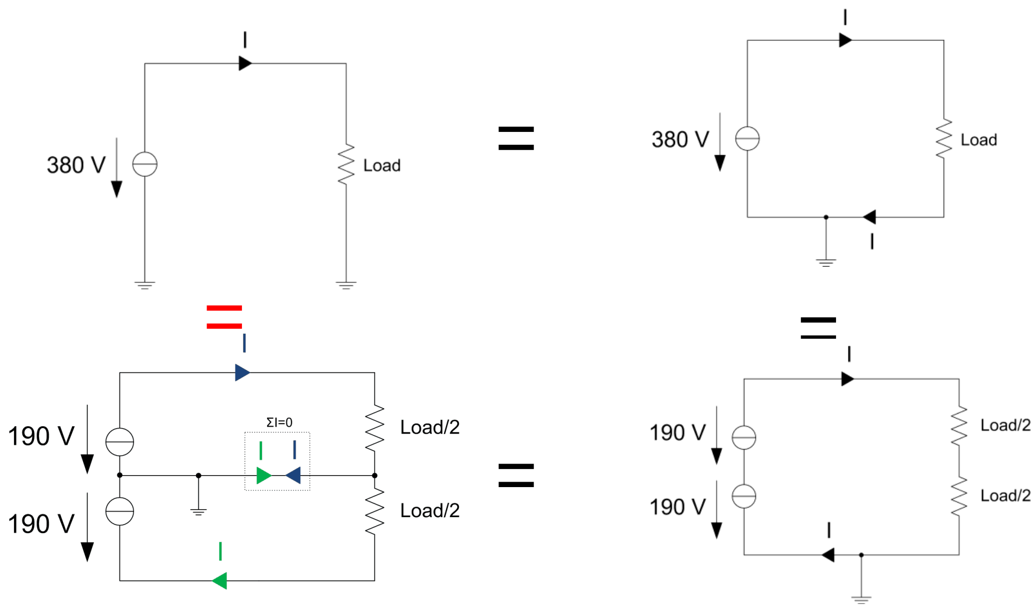

Figure 11: Investigation of ±190Vdc topology in comparison with the +380/0 Vdc topology

In this section, we investigate the difference between the ±190 Vdc topology and the +380/0 Vdc topology. As shown in Figure 11, we see that if we assume a conductor as a neutral for the 380/0 Vdc, then the two topologies are equivalent in terms of network losses. So, all our investigations in the previous sections should apply for the ±190 Vdc topology as well. In terms of costs, in both topologies, the cables should have the same ampacity, as the same current flows. The difference is that in the ±190 Vdc case, the voltage is lower so the need for insulation is lower as well. However, given that both ±190 Vdc and 380 Vdc are low voltages, we do not expect a cost difference due to insulation for the two cables. Another alternative is to directly ground the system in the 380/0 Vdc topology, avoiding a return conductor. However, this is not recommended for safety considerations and protection (leads to contact corrosion and voltage mismatch if the grounding is not carried out properly).

Cost Estimates (draft)

AC Microgrid

Below are our cost estimates for the necessary components for the AC microgrid.

Cable Type	# Conductors	Ampacity (A)	Length (ft) (total length for all conductors of same type)	Price
3x120 mm2 Al XLPE	5/0	250	3101	$2,697
1 X 120 mm CU XLPE Twisted Cable	5/0		1034	$5,581
4x6 mm2 Cu	8	44	394	$666
3x70mm2 Al XLPE	3/0	185	1034	$2,428
1X54.6 mm2 AAAC Twisted Cable	2/0		345	$270
3x50 mm2 Al	1/0	145	295	$151
1x35mm2 Cu XLPE	1		197	$217
4x25 mm2 Cu	2	108	394	$638
4x6 mm2 Cu	8	44	394	$167
4x16 mm2 Cu	4	82	394	$400
			Total	**$13,215**

Table 2: Cost of AC line equipment for the AC microgrid

Converters	Voltage	Hardware	Assumptions	Price
DC/AC PWM 40 kVA - 1900 Amp-hr -1000 kWh - 500 kW	400 Vdc / 400 Vac	Battery & Off-grid Inverter	$1.60/Watt[1] (Inverter)	$64,000
AC/DC PWM 20 kVA	1000 Vac/500 Vdc	Wind Turbine Rectifier	Use two (2) 15 kw modules and one Frame/Rectifier from Starline Enterprises[2]	$26,000

[1] http://www.gogreensolar.com/products/satcon-powergate-plus-pvs-100-100kw-480vac-grid-tie-inverter-transformer

[2] Pricing from Dave Geary of Starline Enterprises, Frame and Controller $20K + each 15 kW rectifier module is $3,000.

DC/AC PWM 20 kVA	500 Vdc/400 Vac	Wind Turbine Inverter	$.40/Watt[3] Installed	$8,000
DC/AC PWM 10 kVa	400 Vdc/400 Vdc	PV inverter	$.40/Watt[4] (Inverter)	$4,000
DC/AC PWM 10 kVA	400 Vdc / 400 Vac	Fuel Cell inverter	$.40/Watt[5] (Inverter)	$4,000
DC/AC PWM 3 kVA	400 Vdc / 400 Vac	PV inverter	$.46/Watt[6] (Inverter)	$1,380
DC/AC PWM 40 kVA	400 Vdc / 400 Vac	Microturbine Inverter	$.40/Watt Installed	$16,000
AC/DC PWM 40 kVA	1000 Vac/500 Vdc	Microturbine Rectifier	Use three (3) 15 kw modules and one Frame/Rectifier from Starline Enterprises	$29,000
			Total	**$152,380**

Table 3: Cost of converter equipment for the AC microgrid

DC Microgrid

Below are our cost calculations for the necessary components for the DC microgrid.

Cable Type	# Conductors	Ampacity (A)	Length (ft) (total length for all conductors of same type)	Price
2x120 mm2 Al XLPE twisted cable	5/0	455.75	2067	$1,798
2x6 mm2 Cu	8	80.212	328	$139
2x70mm2 Al XLPE	3/0	337.255	689	$539
1x54.6 mm2 AAAC Twisted Cable	2/0		345	$270
2x50 mm2 Al	1/0	264.335	197	$101
1x35mm2 Cu	1		98	$217

[3] http://www.windenergyfoundation.org/wind-at-work/wind-consumers/wind-power-your-home
[4] http://www.gogreensolar.com/products/satcon-powergate-plus-pvs-100-100kw-480vac-grid-tie-inverter-transformer
[5] http://www.gogreensolar.com/products/satcon-powergate-plus-pvs-100-100kw-480vac-grid-tie-inverter-transformer
[6] http://www.gogreensolar.com/products/sma-sb-3000us-sunny-boy-grid-tie-inverter-3250w-with-dc-disconnect

XLPE				
2x25 mm2 Cu	2	196.884	197	$319
2x6 mm2 Cu	8	80.212	197	$83
2x16 mm2 Cu	4	149.486	197	$200
			Total	**$3,667**

Table 4: Cost of DC line equipment for the DC microgrid

Converters	Voltage	Hardware	Assumptions	Price
AC/DC **100 kVA**	20 kV/400 Vdc	Rectifier	Use seven (7) 15 kw modules and one Frame/Rectifier from Starline Enterprises[7]	41,000
DC/DC 40 kVA - 1900 Amp-hr -1000 kWh - 500 kW	400 Vdc / 380 Vdc	Battery Converter		$4,886
AC/DC PWM 20 kVA	500 Vdc/400 Vac	Wind Turbine Rectifier	Use two (2) 15 kw modules and one Frame/Rectifier from Starline Enterprises[8]	$26,000
DC/DC 10 kW	400 Vdc/380 Vdc	PV inverter	Alpha System 14kW, 380V to 48V; 19/23" universal mount system - From Pricing Sheet Attached - Extrapolated Using $349/kW of Capacity	$3,490
DC/DC 10 kVA	400 Vdc / 400 Vdc	Fuel Cell inverter	Alpha System 14kW, 380V to 48V; 19/23" universal mount system - From Pricing Sheet Attached - Extrapolated Using $349/kW of Capacity	$3,490

[7] Pricing from Dave Geary of Starline Enterprises, Frame and Controller $20K + each 15 kW rectifier module is $3,000.

[8] Pricing from Dave Geary of Starline Enterprises, Frame and Controller $20K + each 15 kW rectifier module is $3,000.

DC/DC 3 kVA	400 Vdc / 400 Vac	DC-DC Converter	Alpha System 14kW, 380V to 48V; 19/23" universal mount system - From Pricing Sheet Attached - Extrapolated Using $349/kW of Capacity	$1,047
AC/DC PWM 40 kVA	1000 Vac/500 Vdc	Microturbine	Use three (3) 15 kw modules and one Frame/Rectifier from Starline Enterprises[9]	$29,000
			Total	**$82,913**

Table 5: Cost of converter equipment for the DC microgrid

Total Costs AC Microgrid: 165,595 USD

Total Costs DC Microgrid: 86,580 USD

Total Cost Savings: 79,016 USD

As we observe from the above tables, the major cost component for both microgrids are the AC/DC or DC/DC converters. In total, we see that the DC microgrid results to about USD 79,016 less costs. This is about 50% less costs for building a DC microgrid in comparison with an AC microgrid.

AC Microgrid 120 V – 60 Hz

Our studies have been carried out on a 400 V / 50 Hz AC microgrid, as this was the only widely available fully documented model in the literature. CERTS microgrid is also running on 480 Vac (phase/phase), with transformers 277/120 Vac (phase/neutral) to supply local loads. For microgrid voltage levels similar to the CERTS microgrid we do not expect significant differences from the results presented in this study.

Although 120 Vac is the standard residential voltage for the US, operating a microgrid at 120/208 Vac would be improbable, as it would lead to substantial losses. In any case, in this section we attempt some estimates for the losses in such a case. The AC microgrid losses are expected to increase for two reasons. First, due to the lower voltage, and, second, due to the higher frequency, which results in higher reactance, i.e. $X=j*2\pi f*L$.

[9] Pricing from Dave Geary of Starline Enterprises, Frame and Controller $20K + each 15 kW rectifier module is $3,000.

For short distances a line can be approximated as a series impedance Z=R+jX. The losses are equal to $S_{losses} = I^2 R + j I^2 X$. Due to the higher frequency, the reactive losses due to X will be 20% higher. Due to the lower voltage 208 Vac phase/phase vs. 400 Vac, for the same amount of power, we need twice the amount of current. Assuming similar conductors to keep infrastructure costs the same, the current will increase twice and the losses four times.

So, for the same conductors, comparing with Fig. 5, there will be an additional loss of 30,000 kWh, which results in costs of 6,000 USD per year. This doubles the annual costs for losses of the AC microgrid. If new conductors, with lower resistance are selected, this will increase the capital costs. A detailed study is necessary in this case to determine the necessary lengths of each conductor type and identify the increase in these costs.

Conclusions

Concluding this application, we find that DC microgrids are always superior to their AC counterpart with respect to the total network losses. They result in up to 90% less losses and have the potential to lead to up to 20% – 30% cost savings. We have also observed that the load power factor plays a significant role for the efficiency, and replacing AC loads with low power factor with DC loads leads to higher energy savings.

In terms of efficiency gains due to network and conversion losses, a DC microgrid is always preferable, independent of the load mix, i.e. how many loads are native-AC and how many native-DC. The final decision for a retrofit, however, is also dependent on the costs. Given that several loads and Distributed Generation are native-DC, we expect that a DC microgrid will also be cost-effective for new microgrids, especially if these are off-grid or usually operated in islanded mode (thus avoiding the high capital costs and bidirectional losses of the AC/DC converter at the interface with the AC grid).

As seen in our cost calculations, for new microgrids, building a DC microgrid results to about 50% costs less than its AC counterpart.

On the other hand, it is not clear if retrofitting existing grid-connected microgrids is economically attractive based only on the efficiency gains, as the total losses amount to about 3%-6% of the total energy consumed. Still, additional research is necessary to identify additional benefits of DC microgrids, especially with respect to resiliency and power quality, and determine if such advantages can substantially contribute in making DC microgrids retrofits economically attractive for grid-connected applications as well.

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[2] DigSilent Powerfactory. Online: http://www.digsilent.de/

Application #2—High Survivability DC Microgrids

Introduction

Power systems have notably been susceptible to severe environmental conditions during the past decade. Events such as hurricane Katrina in 2005 and hurricane Sandy in 2012 have exacerbated some of the weaknesses associated with our modern power grid to severe events. Other less extreme events such as ice storms, snow storms, downed tree limbs, and small animals often result in more localized power outages that can impact customers for minutes to days. The utilities have developed schemes to clear smaller system faults.

Increasing survivability to unplanned damaging events is important to the military as well as commercial utilities. In particular naval ships and forward operating bases are two examples for which this characteristic is important.

Approaches to survivability can be classified into two classes, proactive and reactive (protection and restoration) [1]. For the purposes of this discussion survivability will be considered in the context of resiliency to a damaging event. From this point forward a damaging event and an event will be synonymous for this discussion. In contrast to reliability, resiliency implies events that have low probability but high consequence.

Increased survivability can be achieved by further reducing the likelihood of an event that results in system damage, increasing the ability of the system to withstand an event, and reducing the consequences associated with an event. The following sections discuss DC microgrids and approaches to address survivability in the context of these three approaches.

Event exposure reduction

Reducing or even preventing exposure to an event would be considered a proactive step. An approach to reducing the likelihood of an event would be: only constructing power systems in areas that would not be exposed to an event such as a hurricane, ice storm, etc. Utilities use a similar approach by trimming tree limbs in the vicinity of power lines. These and other methods can help reduce the risk of damage to power systems but are not always feasible due to existing inhabitants for the utilities or due to the mission needs of forward operating bases and Naval ships. For systems such as these alternative approaches must be taken to increase survivability.

Ruggedness

Increasing the ruggedness of a power system would also be considered a proactive step. In cases where reducing exposure to potentially damaging events is not possible an alternative is to increase the ruggedness of the microgrid. This can be considered for events internal and external to the microgrid.

Each individual component in the microgrid can be designed to be more rugged to ensure that it will survive an event. This can include moving distribution lines underground as well as redesigning generation, storage, and load components so that they are capable of continued operation through during floods, ice, etc. For some events this may be impossible, however, in all cases the cost will have to be considered. At a high level DC microgrids would not be expected to have an advantage over AC microgrids for this approach.

External events are events that occur outside the microgrid but within connected power systems. In this case the power electronic interface between the microgrid and the other systems would act as a firewall and/or a disconnect to ensure that the disturbance does not propagate into the microgrid [2,3,4]. Preventing events that occur internal to the microgrid from propagating out to other power systems will also be prevented by the power electronic interface. DC microgrids may have an advantage over AC microgrids due to the ability to filter out higher frequency content that may pass through AC/AC connections.

System protection devices also increase the survivability. This includes fusing, circuit breakers, and protection schemes. AC microgrids have advantages when it comes to protection considering many decades of development have been devoted to the techniques used by utilities today. A significant advantage for AC systems is the zero crossing of the current which enables arc extinguishing. Recent advances in DC protection devices are starting to make improvements but at high current and voltage levels the devices can become quite complex often involving techniques such as using magnetic fields to break the arc.

Use of power electronics as protection devices is also a consideration. This involves converter designs that detect fault currents followed by limiting or interrupting the current [5]. This approach does not appear to provide advantages for either AC or DC systems and can decrease the reaction time for eliminating the faults.

Utilization of ring-buses and fault location schemes continue to be developed to improve the ability to provide both fault protection and identification of fault locations [6].

One last approach to increasing ruggedness may be to use forecasting. With this approach portions of the power system may be shut down a priory to minimize damage caused by energy contained in the power system itself. Bringing the power system back on line following an event will have to be carefully staged to address unknown faults in the system.

Consequence reduction

Both proactive and reactive steps can be taken to reduce consequences associated with an event occurring to a power system. For the purposes here consequence reduction equates to minimizing the time that loads are without power and minimizing the percentage of loads that are without power. The latter should involve prioritization of loads to ensure that investments address the most critical loads first. Local energy storage in the form of batteries, capacitor banks, and back up generation are a few examples of components that may be added to a system to allow continued operation of loads. These may even be targeted towards the most critical loads thereby addressing the most severe consequences. Ensuring the survivability, simplifying maintenance, and maximizing the efficiency of these added resources are important steps to enabling and maintaining power to loads for the greatest amount of time following an event. DC microgrids would have an advantage over AC systems, regarding efficiency, if the energy storage and the loads were matched DC components. Otherwise the advantages would be system and load dependent.

Events such as flooding from hurricanes would likely damage most components in a power system regardless of the AC or DC characteristics. Installation and protection schemes that would prevent exposure of components to damaging conditions, such as elevating generators above the flood plane, will be important for continued operation.

Reduction in the outage time or geographical area covered by the outage are additional approaches to addressing the consequences of an event. Outage time may be reduced by simplifying the process for bringing system generation back on line and clearing or isolating existing faults. AC power systems may have an advantage regarding the clearing of transient faults. Otherwise the advantages of one microgrid type over another are less clear.

Isolating faulted components or damaged areas of a microgrid can be addressed utilizing automatic techniques already implemented by utilities today. However, microgrid networks either AC or DC may enable more robust approaches though advanced controls [8] or by enabling topology changes [1,7,9]. This may include earlier detection of a problem or enhanced ability to prevent cascading outages.

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Application #3—Low Power Network with Differentiated and Automatically Evolvable Power Quality and Reliability

Challenges: Achieving systems of 100 kW of capacity

Brief Description— DC has always dominated communications networks. Telephone service was reliably powered for generations with a low power DC grid that reached virtually every home and business—a highly resilient system designed to survive extended periods without grid power. More familiar today, Power Over Ethernet (PoE) networks are ubiquitous in commercial buildings. Such networks, or similar ones, can be beneficially extended to serve other sensitive loads beyond communications, in an efficient and reliable fashion while eliminating the need for individual power supplies. This includes end uses such as computing, medical devices, entertainment, control systems, other electronics, emergency equipment, etc. - indeed a few non-communications PoE devices, such as lighting, are already on the market. The technology under consideration here delivers both power and data. It could be a low power (<100 W loads) network like PoE or USB, or some higher power high PQR system. Automatic and evolving segmentation of critical loads would provide backup power on a device-by-device level eliminating the need for and providing greater flexibility than individual battery backups. A few large battery backups would require less maintenance cost than many individual units. Segmenting power quality sensitive loads to PoE networks and keeping them off of normal utility service can makes industrial and building control systems more robust while permitting lower power quality service to the much larger non-sensitive loads.

Base Case for Comparison— Devices powered individually using AC/DC power supplies connected to a normal 120V AC supply with critical loads individually backed up. Smart devices individually managed, and data collection independent of power supply..

Is This Uniquely a DC application?—No. The devices of interest are native DC, but they are generally supplied now with standard AC service.

Potential Impacts— Assessing the cost-benefit of these microgrids has two levels. First, the PQR of service delivered to the critical load, or sub-load. And second, the implications of its existence for other loads and systems. As with other DC networks, there are peripheral effects worthy of consideration, such as improved heat management, both within devices and buildings.

The scenarios described below are considered general.

The backbone of DC microgrid is either powered by centralized ac/dc rectifiers (denoted as Scenario A) or the local dc generation such as solar or fuel cell assisted by battery storage systems (denoted as Scenario B), and dc/dc converters are used to power individual native dc loads;

1. The backbone DC voltage can be 48V[1] or 380V;
2. The AC loads are served directly by the existing AC power supply;
3. The ac/dc rectifiers needed for individual dc loads in an existing system are replaced by dc/dc converters in DC microgrid that are converted from the existing system.

Reliability—primary benefit

- Positive—
  - For Scenario A, greatly reduced device outage statistics (SAIDI and/or SAIFI, or suitable modification) because: back-up service is more easily managed centrally than individually for small power high value added loads, smart environment enables heterogeneity and prioritization of service, control of other larger devices enhances the reliability of its service, better heat management improves device reliability.
  - For Scenario B, the local solar generation or other dc sources such as fuel cells, with battery systems will potentially enhance the reliability of the DC microgrid. Otherwise, the difference in reliability will stay the same.
- Negative— Overall reliability dependent on effective maintenance of the DC microgrid including the reliability of the primary source of power, e.g., AC-to-DC power converters or the local generation sources that supply the DC system

- **Power Quality—primary benefit**

For Scenario A, due to the lack of power quality features designed for the DC native loads, the power quality features have to be equipped with the backbone rectifiers to accommodate the non-sinusoid currents provided the high volume of DC native loads to be installed. For Scenario B, this issue will be eliminated.

- Positive—Fewer excursions outside of CBEMA/ITIC (for DC relative to AC) because of isolation from AC system and generally lower power loads
- Negative:
  - For Scenario A, i.e., the backbone of DC microgrid is powered by centralized ac/dc rectifiers. If the DC backbone is used directly as power source, the power quality is expected to be lower [2] because this is inherent to power electronics of high capacities. For lower voltage loads powered via low capacity dc/dc converters, power quality issue is not a concern.
  - For Scenario B, i.e., the backbone of DC microgrid is powered by local generation, there is no power quality issue compared to the system powered by AC supply.

- Energy Efficiency—secondary benefit

[1] This is how people most commonly reference PoE and similar systems. The voltage level for such systems can vary between 43 and 57 V. Since PoE is the focus of this study, other applications such as 24V EMerge standard are not considered.

[2] The total harmonic distortion (THD) for (1) a 6-pulse rectifier is between 30% and 50%; (2) a 12-pulse rectifier between 10% and 15%; and (3) a PWM-rectifier between 3% and 5%.

- Positive—Lower losses because centralization of power conversion improves efficiency and most power conversions are avoided entirely. Lower cooling demands if power supplies are removed from the building.
- Positive – if 380V DC is adopted, the losses associated with delivery may be reduced for both Scenarios A and B compared to AC power supply of existing buildings (110V or 220V)[3].
- Positive – In both Scenarios A and B, the ac/dc rectifiers needed for individual dc loads in current ac systems will be replaced by dc/dc converters in DC microgrid[4].
- Negative—Potentially higher resistive losses in low voltage systems

- **Operating Costs—secondary benefit**
  - Positive— Avoids cost of managing individual back-up systems and several alternative PQR or efficiency schemes
  - Negative—N/A
  - It is difficult to tell the difference in operating costs[5] for the dc microgrid and the existing system.
- **Capital Costs—primary benefit**
  - Positive— Avoided cost of purchasing many individual power supplies and UPSs . Inherently safe plug-and-play technologies can reduce installation complexity and labor costs.
  - Negative— Potentially costly and disruptive network installation, if not preexisting or intended for data communication, e.g. if data communication is wireless.
- **Engineering Costs—primary benefit**
  - Positive—Networks are typically highly standardized, and if suitable standards are established, local engineering is minimal. Communications to manage power distribution enable functions not possible with traditional technology, AC or DC, such as plug-and-play operation for local generation, storage, and critical load selection.
  - Negative—N/A
- Environment
  - Positive— For Scenario B (A), (potentially) lower its carbon footprint, and reduce battery replacement.
  - Negative—N/A
- Safety
  - Positive—Low voltage enables physical reconfiguration while energized
  - Negative—N/A

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[3] The loss reduction can be estimated assuming that the same amount of power can be provided with half of the current if the voltage is doubled. Assuming that all the loads are of single phase, then the loss reductions I^2R will be 90% for a change from 120VAC (line to neutral) to 380VDC, and 67% from 220VAC (line to neutral) to 380VDC.

[4] For the AC distribution that has to use rectifiers and dc/dc converters to power the DC loads, a total efficiency of 88~93% can be achieved. For Scenario A that requires both rectifiers and dc/dc converters, the efficiency may stay the same. For Scenario B, the efficiency using the PoE can be increased to 92~95%.

[5] Maintenance should be cheaper for DC as devices could be plug-and-play, even for storage and generation. The associated cost reduction is, however, difficult to quantify.

Application #4—Converting AC Systems to Hybrid AC/DC Systems

Introduction / Background

Presently, AC distribution systems are the predominantly utilized method for distributing power. This has been true since the invention of AC synchronous generators and AC induction machines [1]. AC machines have been found more efficient, requiring less maintenance, and have relatively higher power densities than DC generators and motors. However, with the growth in DC loads from switched mode power electronics in machine drives, automation, lighting, air conditioning, and computational loads reviews of potential benefits in DC are underway. In this document, a review of the conventional approach of AC systems and DC systems is provided as well as four other possible options to distribute AC and DC power using the same distribution system or electrical installation in a wire.

Option 1: Traditional AC with conversions to DC

The most implemented approach for building systems is a AC voltage with conversion steps to the DC components such as loads. These loads either use DC internally or the AC is first rectified and then inverted back to AC at a different phase, magnitude, and frequency in order to control the variable AC drives. Some example loads that require DC are computers, laptop and cell phone chargers, LED and LED lighting systems. In all these loads, 120V-60Hz AC line voltage is first rectified and filtered with a DC link capacitor. Then, this DC voltage is converted to 25V, 12V, 5V, and/or 3.3V DC levels using buck type DC/DC converters or flyback DC/DC converters. DC/DC step-down conversion and the number of DC voltage levels depend on the computer power supply architecture and the needs of the computer electronics. In the case of LED lighting systems, again, AC line voltage is rectified and stepped down to 3-5V and applied to the parallel connected LEDs or a higher DC voltage is applied to a series connected string of LEDs. Another popular example of DC load is the electric vehicles (RV). Instead of converting AC to DC and then boosting the rectified voltage, a DC distribution system would be more efficient for EV charging applications. Even with the wireless power transfer based EV chargers, first DC input is needed for the high frequency inverter inputs.

With regards to the loads with AC machines, such as refrigerators, air conditioners, and washers/dryers, AC machines working with the line voltage/frequency have historically been the most popular. However, with the recent advancements in power electronics based adjustable speed/torque drives, the efficiency and effectiveness of AC machines could be improved. For example, in “direct-drive” AC systems, all mechanical reduction mechanisms such as gear boxes, chains, and/or belts since the speed/torque of the machine can be reduced or increased electronically. This eliminates the noise, improves the efficiency, provides a longer lifetime, improves reliability, and provides faster and precise speeding and positioning. Recently, in addition to washing machines, there is a trend to have air conditioner compressors, fans, refrigerator compressors, and almost all the rotational loads directly driven. Direct drive and adjustable speed drives again require the conversion of AC line voltage to DC and then back to AC in a controlled manner.

Another conversion stage becomes necessary with renewables. The renewable energy generation from solar, wind, and ocean energy systems are rapidly growing. Among these, solar inherently generates DC output voltage which is usually converted to 60Hz AC for utility interconnection. These 60 Hz systems require large sizes of expensive filtering systems and usually transformers for increasing the voltage (if needed).Wind and ocean energy harvesting systems usually have AC generators; mostly permanent magnet synchronous generators or induction generators due to the variable speed/torque nature of the mechanical drive sources (wind speeds, ocean tidal streams or up and down motion of ocean wave energy harvesters with linear generators). Due to the variable and intermittent input of these energy systems, the output voltage is also variable magnitude / variable frequency and usually intermittent. Therefore, a back to back rectifier + inverter system is usually employed as a power electronic interface when connected these renewable energy sources to the grid. In many cases, at the DC bus (rectifier output / inverter input) a DC energy storage system (battery packs, ultra-capacitors, etc.) is employed to suppress the long and short-term generation fluctuations.

Benefits of DC and Hybrid AC-DC Distribution Systems

There are several benefits of DC distribution for loads that use or need DC internally. These advantages can be summarized as:

1) AC to DC conversion at low power systems can be inefficient when several small rectifiers are distributed within appliances. In most cases, charger adaptors, computer power supplies, and other rectifier based loads do not have the highest quality of power supplies (due to the low power consumption levels but when aggregated, the total amount can be fairly large) and they are usually inefficient.
2) With the AC distribution, usually transformers are required to convert higher voltage AC distribution (usually 4, 12, or 17kV levels) to a reduced electrical installation level AC voltages (usually 120, 208, or 240V). These AC distribution transformers operate at 60Hz, they are very bulky, heavy, expensive, and inefficient. DC distribution would eliminate the need for AC transformer units.
3) Uninterruptible power supply (UPS) systems, when connected to AC distribution systems, are not very efficient due to the high number of power conversion stages (AC to DC and then DC to DC for charging and backwards when discharging). However, with the DC distribution, a single-stage bi-directional DC/DC converter would be good enough.
4) With the DC distribution, overall amount of copper needed for the distribution and installation could be reduced due to the elimination of 60Hz transformers and the number of wires needed.

Option 2: Simultaneous AC and DC distribution by using neutral and earth ground wires for DC system

One approach to simultaneously transmit AC and DC over the same infrastructure is to use the neutral and ground wires of an existing AC distribution system [2]. In this approach, phase and neutral of an existing AC system continue to provide AC voltage as needed and the neutral and ground outlets and wires of the existing AC installation are used for carrying the DC voltage. The neutral of the AC line is the negative port of the DC system whereas earth ground wire is the positive port of the DC system.

This system proposed in [2] is implemented to an existing AC distribution system as shown in Figure 1. From Figure 1, it is seen that the input can be a single or split phase. A rectifier (followed by a buck DC/DC converter) is connected at the 208V AC system. Then, 120V is obtained and used between the phase and neutral wires as conventional and the rectifier system output is distributed through the neutral and ground wires of the AC system. The wall outlet port configuration of this system is represented in Figure 2 whereas Figure 3 illustrated how the AC and DC loads can be plugged-in using the same wall outlet and plug structure. Currently, low voltage DC (24VDC) is being reviewed for this application.

Although this approach is theoretically very feasible, there will always be some inherent imbalance within the building that results in non-zero neutral current. As a result, AC current will be present on the neutral wire (and corresponding AC voltage), which is the return path for the DC. The neutral current due to imbalances can only be eliminated by a power electronic converter based shunt active-filters (or active phase balancing systems), which can take the excess power from one phase and injects it to the other phase to balance the phases.

Another potential challenge is the utilization of the ground wire. Applying DC voltage to this wire or using it as a positive port for the DC distribution would change the potential of the earth ground - ground wire. Ground should ideally have 0 V potential at all times (as best possible). Without this voltage, protection functions in the case of a fault and if the people are for example touching the faulted appliances with metallic bodies (refrigerator, washing machine, etc.) may not be available. Having some current on the ground wire will also kick in the ground fault circuit interrupters (GFCIs) since these are also based on sensing the ground current. Computers and many electronic brains (microcontrollers, digital signal processors, etc.) in appliances may need an earth ground reference to accurately generate the logic 1 and logic 0 (3.3V or 5V for logic 1 and 0V for logic 0) and all the other outputs. In most power electronic applications, for example in computer power supplies, digital ground is connected to the analog ground which might be connected to the earth ground if not floating otherwise (would depend on the power supply architecture) If you can’t supply an accurate earth ground, the output of these devices may also oscillate. While this design could save a reduced cost in not requiring additional lines (separate DC distribution), actual efficiency gains may be minimal, as power supplies to convert to the DC voltage is still needed. DC/DC converters could link the DC renewable resources instead of a multistage system.

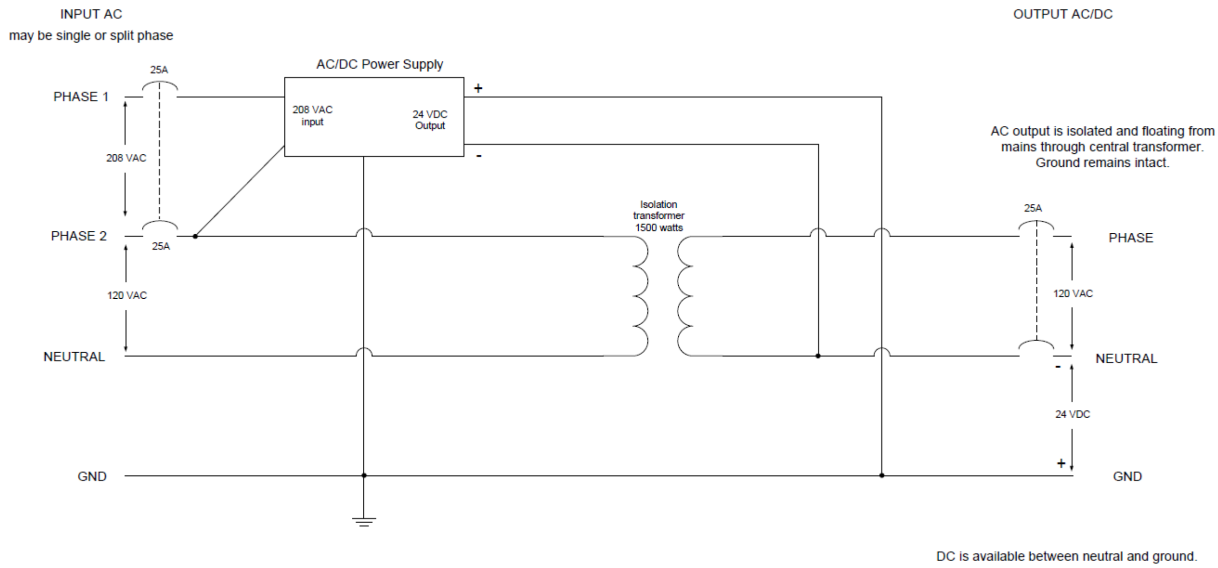

Figure 1. Hybrid AC/DC distribution option proposed by Nextek [2].

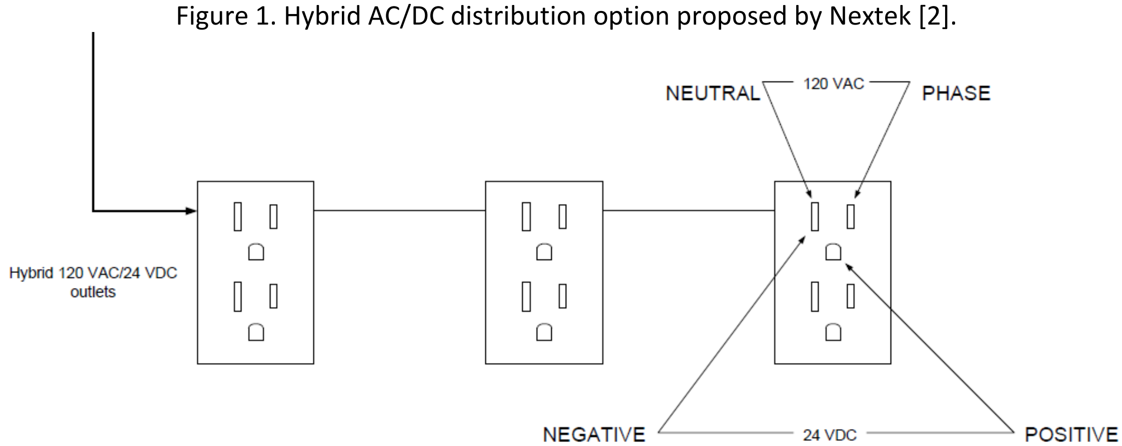

Figure 2. Wall outlet port configuration of the Nextek hybrid AC/DC distribution system.

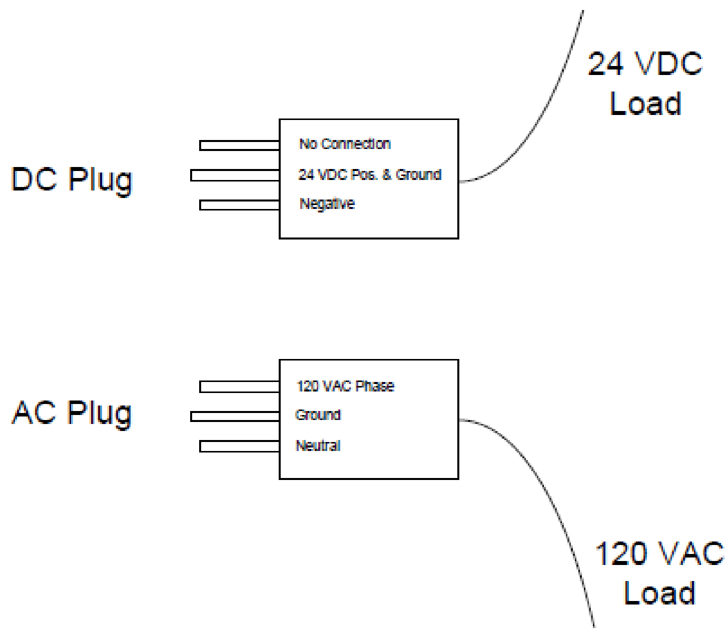

Figure 3. Plugging-in the AC and DC loads with the same plug and wall outlet.

Option 3: Additional, independent DC ceiling grid installation:

Proposed by the E-Merge Allinace [3], which is claimed to be an open industry association, the DC ceiling wiring is used to bring the AC power into the existing building architecture without performing the major rewiring work that would normally require the removal or alteration of the building walls to have the DC distribution wires installed. This approach can reduce the complexity, reduce the installation time, and is a cost-effective solution without interfering the building existing AC wiring my any means. Since DC distribution has its own wires, no existing AC wires (phase, neutral, ground) are used for the DC unlike the previous option. Therefore, it is a simple and flexible reconfiguration. This approach can bring power to the DC devices/loads while providing the integration of solar panels, wind, fuel cell, and energy storage systems such as batteries [4]. The overall architecture is illustrated in Figure 4.

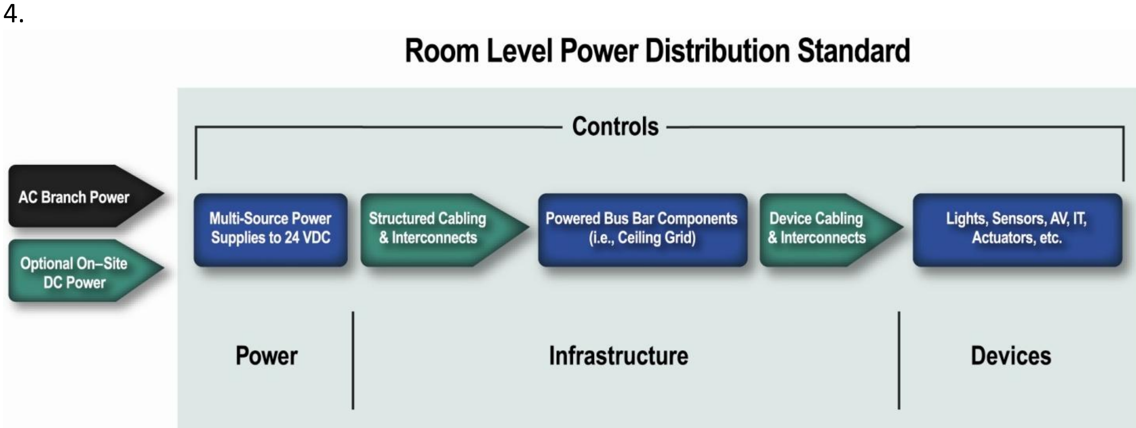

Figure 4. DC distribution system architecture block diagram of the E-Merge Alliance [3].

In this system, 24V DC distribution is utilized due to the fact that power over 30V is not considered "safe" when conductors would normally have to be enclosed in conduits, metal jackets, or other forms of enclosure. Therefore, keeping the DC voltage at 24V allows ceiling wiring to be flexible, cost-effective, modular, efficient, and safe. According to National Electric Code (NEC), Class 2 circuits are power limited to 100VA; therefore, a Class 2 24V DC circuit can deliver up to 4.16A of current and provide reasonable protection from electrical shock and fire initiation. Since the power is limited to 100W DC, it is not expected to have significant line losses in the DC distribution system. Furthermore, instead of three, only two wires are needed for DC distribution. Additionally, no wiring is required to be encased in metal jackets, junction boxes, etc. and these features typically keep the wiring and installation cost low. The proposed system architecture block diagrams are given in Figures 5 and 6.

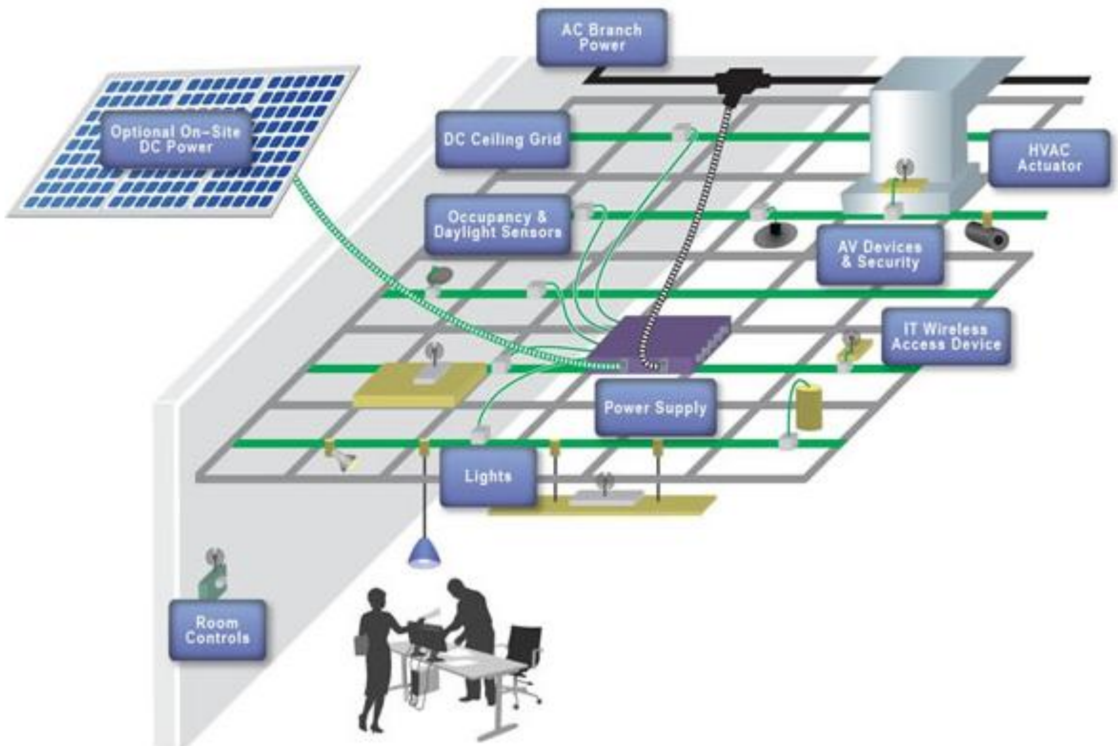

Figure 5. Ceiling DC distribution system architecture block diagram [3].

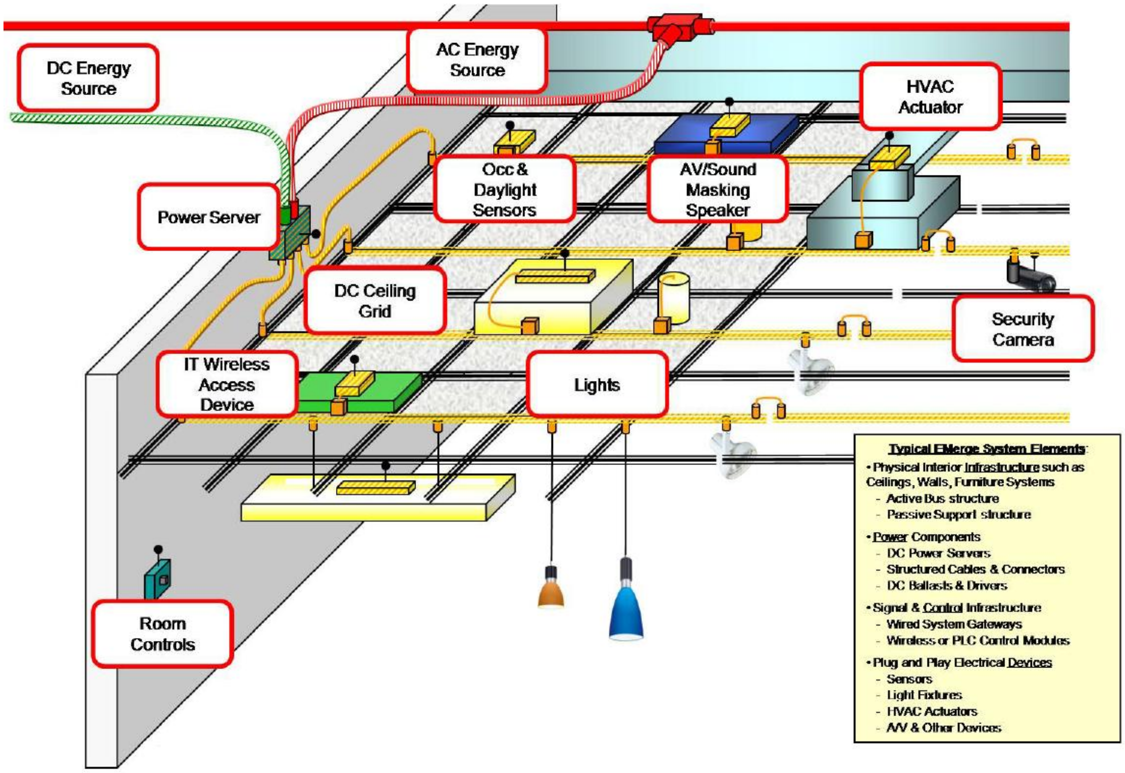

Figure 6. Ceiling DC distribution system architecture block diagram [4].

Option 4: Simultaneous AC and DC distribution using Multiplexing / Demultiplexing:

This concept facilitates the Pulse-Width Modulation (PWM), Time-Division Multiplexing (TDM), and Power Multiplexing and Demultiplexing (MUX/DEMUX) concepts to chop, combine, transport, separate and reconstruct both AC and DC power over a single existing wire [4]. The overall conceptual block diagram of the system is shown in Figure 7. PWM is an electronic power switching technique for regulation of AC and DC power in an efficient way. The AC power's sine wave is chopped into many slices through fast electronic on/off switching (tens of thousands of on/off cycles per second). The chopped wave is filtered and the resulting sine wave is applied to the electrical load. TDM is a concept where multiple signals are simultaneously transmitted over a single information medium such as a wire. The physical medium is time-shared amongst all signals through the allocation of cyclical timeslots of fixed length that are exclusively dedicated to each respective signal. The building blocks of TDM buses are the MUX and DEMUX devices. A MUX selects one of many input signals and forwards the selected input into a single output line. A DEMUX performs the inverse, by separating the signals at the input and forwarding them on to separate output lines. AC and DC power sources are each individually supplied to the system and chopped at the same frequencies. The AC "off" periods correspond to the DC "on" periods. The power sources are then multiplexed through a high frequency power MUX and applied to an existing building wiring infrastructure (the TDM power bus).

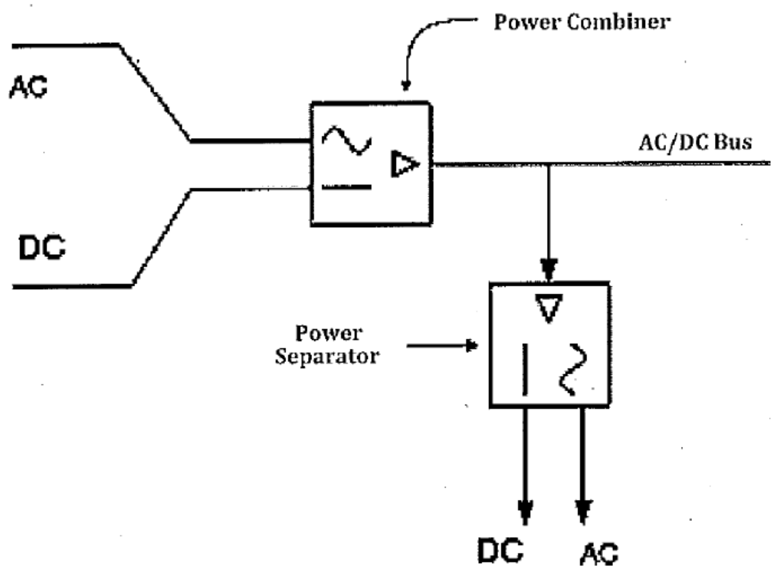

Figure 7. Conceptual block diagram of multiplexing / demultiplexing based simultaneous AC and DC distribution system [5].

At utilization a device separates the DC from the AC via a high frequency power DEMUX. The resulting separated AC and DC signals are reconstructed at voltages roughly half of the source voltages. To compensate for this lower voltage at the load, a transformer can be inserted at the AC source before it is combined with the DC power at the MUX, allowing for the delivery of the required nominal voltage. The DC voltage at the source must be at least double the level of the highest planned load voltage at the utilization load. In Figure 8, a sinusoidal voltage waveform (a), a chopped sinusoidal voltage waveform with ON and OFF periods (b), a DC voltage waveform (c), and a DC chopped waveform (d) are illustrated.

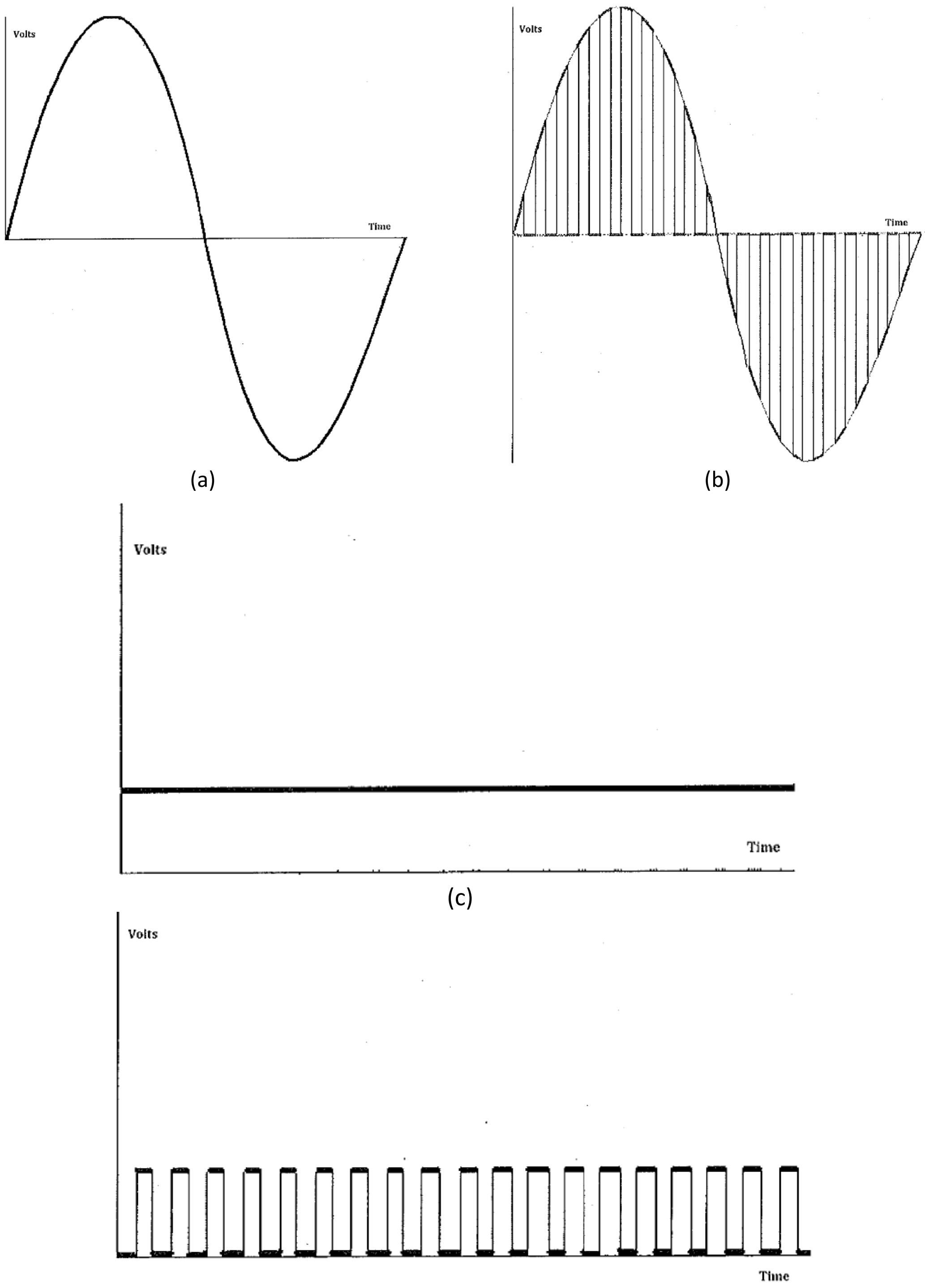

Figure 8. AC voltage source (a), chopped AC voltage with ON and OFF periods (b), DC voltage source (c), and chopped DC voltage with ON and OFF periods (d) [5].

Although this method is feasible and applicable, there are a a number of potential drawbacks. Once the AC voltage is chopped, a LC filter is needed at the receive-end (load side) of the system to reduce the harmonic distortions. This filter should be sized based on the number of switching instants in one period of the AC line voltage. Therefore, in order to reduce the size and cost of the passive components, switching frequency should be increased. However, as the switching frequency increases, switching losses will also increase. Considering this trade-off, an optimal switching frequency should be selected. Similarly, for the DC distribution part, a capacitive filtering should be utilized to average the DC voltage applied to the load so that the load can see a smoother effective DC voltage averaged with respect to the duty cycle and frequency of the chopped DC waveform.

Option 5: DC biasing (offset) based simultaneous AC and DC distribution system:

In this concept, the AC voltage is positively biased with the addition of the DC voltage with a symmetrical drive. This system might be the most suitable for double circuit AC line since there already exist two sets of lines. By positively shifting the ground of one of the lines by the magnitude of the DC voltage and by negatively shifting the positive polarity of the other AC line, both DC and AC energy can be carried on the same system as shown in Figure 9 [6].

The drawback of this architecture is that it inherently requires an existing double AC circuit line distribution system; therefore, although this approach might be feasible for new distribution systems, retrofitting buildings is likely to be a challenge.

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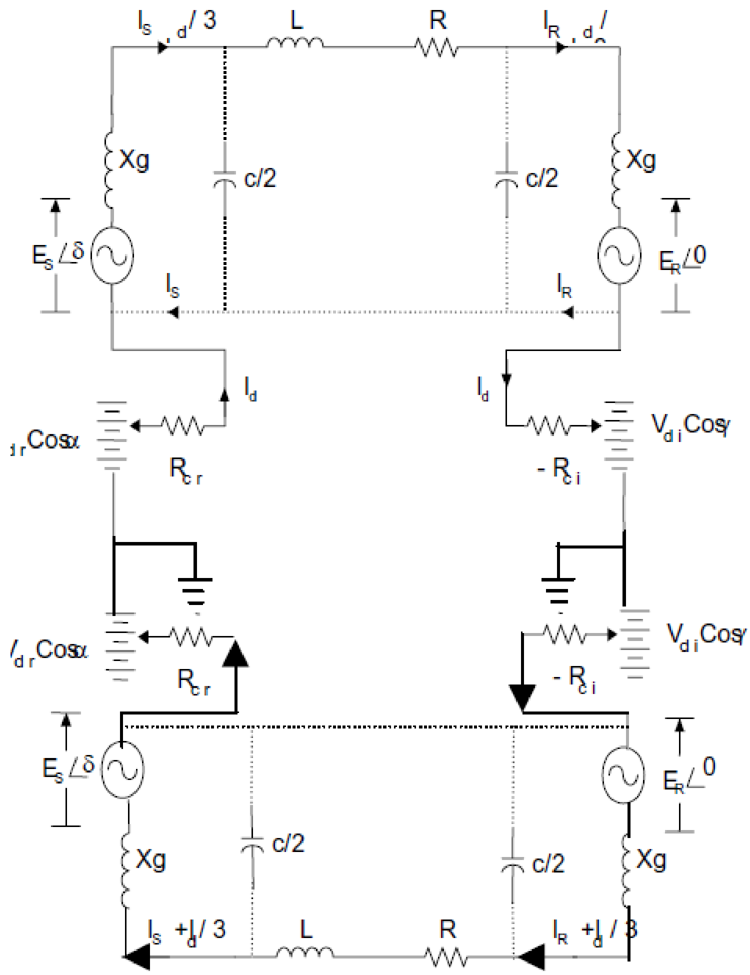

Figure 9. Equivalent circuit of the simultaneous AC-DC power transfer in a double circuit AC line [6].

Application #5—Mobile and Remote Applications

Remote Microgrid Characteristics

Remote microgrids face a unique challenge in that, unlike microgrids within more developed infrastructure, there is no expectation of external energy support. Remote microgrids almost always operate in island mode, making energy adequacy the primary concern. Before addressing the question of AC vs. DC in remote microgrids, it is helpful to consider a few of the common scenarios and characteristics that make remote microgrids a unique challenge.

Perhaps the most obvious remote microgrid scenario is that of an isolated community that has not and may never be reached by the bulk electricity infrastructure. Geography often plays a significant role in preventing the infrastructure from reaching these communities and (in a bit of a chicken-and-egg problem) low population density in the area often makes such expansion financially untenable [1]. These communities can be found in remote areas of both developed and undeveloped countries, leading to widely varying expectations of microgrid performance.

The needs of communities in or associated with developed countries are likely very similar to those of their urban counterparts: dependable, high-quality, and (seemingly) limitless electrical energy readily available at the flick of a switch. The loads of the community would also relatively closely match those of the nearest town or city: electric ovens and ranges, clothes washers and driers, air-conditioners, refrigeration, and electric lighting. These communities are likely to be powered by diesel generation, potentially with attached energy storage and some renewables.

Remote communities in developing countries are in a far different situation. These communities have likely never had ready access to electrical energy and likely have a microgrid in their community to meet basic needs and/or enable basic economic development. There may or may not be a diesel generator, and if there is, it is unlikely to be run continuously or regularly due to expense and availability of fuel [2]. Without electric energy, lighting and heating is often provided by kerosene and biomass, and labor is manual/animal-assisted. A microgrid in such a community might exist to provide night-time lighting, power a pump for drinking water or irrigation, or provide energy to a motor for small-scale manufacturing [3]. In these communities, any semi-reliable electrical energy provides a significant marginal benefit to quality of life and economic productivity.

A third common scenario for remote microgrids, which is something of a hybrid of the two described above, is an expedition camp, similar to a forward military base or surveying/prospecting trip. Like remote communities in developed countries, expedition camps have a greater expectation of and requirement for high quality power. Though some “convenience” loads such as air-conditioning and electric cooking may not be present, there is likely to be specialized “mission-critical” equipment that must operate reliably. However, because expedition camps are temporary, diesel generation may not be an option and fuel resupply may be too infrequent. In addition, the camp may need to relocate frequently during its mission, moving the supporting infrastructure along with it.

AC vs. DC

In light of these three varied scenarios, the question of whether remote microgrids are best served by an AC or DC architecture should be considered carefully. These remote microgrids serve a broad range of functions and loads, and the most suitable approach will likely be influenced significantly by the unique aspects of each scenario. To reiterate, for remote microgrids, energy adequacy is the fundamental challenge.

For remote communities in developed countries, the backbone of the existing microgrid is likely to be an existing diesel generator that produces AC electrical energy. The loads the community purchases and adds to the grid will also likely be AC loads as these are manufactured for the developed world with which they interact. There may be some PV and energy storage on the microgrid to reduce diesel fuel consumption, but unless these sources are providing a significant portion of the energy the community uses, implementing or converting to a DC microgrid in unlikely to offer significant advantages (economic or technical). These types of communities are essentially remote extensions of the developed AC world and are likely best served by conforming to the existing AC standard.

If DC-powered equipment (lighting, appliances, etc.) were to become common in the developed world, it would justify a technical analysis of the costs and benefits to determine if conversion from AC to DC would be beneficial overall. Even for these developed remote microgrids, the cost and delivery of the diesel fuel is significant enough to place a practical limit on the amount of electrical energy used. Any conversion to a DC microgrid would have to offer efficiency gains that would noticeably reduce the concerns of economical energy adequacy.

Barring the commonplace occurrence of DC consumer products in the developed world, a DC microgrid may still offer advantages if the energy source were to change from primarily diesel to renewable generation, particularly if DC energy storage were included. If the most available and/or economical energy source is primarily DC-based but the loads are still AC-based, an inverter would be required to provide energy to the community. The choice of AC or DC would be driven by the economic adequacy question. Is diesel generation still needed to power the community? What is the efficiency of the power electronics involved? How does the cost of the additional equipment compare with diesel fuel costs? What is the payback period?

Remote communities in developing countries have very different needs and expectations. Assuming that dependable diesel generation is likely to remain economically out of reach and that the loads of the community are much lower than those in the developed world, renewable energy, likely PV, will be the essential generation source. Batteries are also likely to play an important role, particularly in providing nighttime lighting. If an architecture similar to this is implemented, a DC microgrid makes the most sense; there is little immediate benefit gained in converting these DC sources to provide AC electrical energy.

There are a few exceptions to using a DC microgrid in remote communities. Light industrial loads such as motors and pumps could play a significant role in enabling economic development, and the most robust implementations use AC motors. DC motors routinely use brushes that require regular replacement and thus are less suitable to remote, undeveloped locations. AC motors or DC brushless motors could be used with the help of power electronics, but this is an additional expense and adds complexity.

Additionally, for some of these communities it is possible that the "remote" microgrid is not very remote, and there could be an expectation that at some point the larger power transmission and distribution system will connect with this existing microgrid. If this were to occur, it would be most advantageous if the existing loads were already AC compatible [4]. Again, power electronics could remedy this AC-DC mismatch at an additional financial cost.

For remote microgrids associated with expedition camps, the choice of AC or DC is least clear. Diesel generation with frequent fuel resupply may or may not be a part of normal operation, and consequentially the significance of renewable generation will also vary. The degree of mobility will vary case-by-case, as will the particular loads that will need powering.

The best general approach in considering expedition camp applications is to determine whether the needs and circumstances of the microgrid are closer to that of the developed or developing world. Developed world expeditions with some connection to fuel supplies and more conventional AC loads (large forward operating military bases, for example) will likely best be served by an AC microgrid architecture [5]. (As in the above discussion, the exception would be when there is a preponderance of DC generation and/or loads, in which case a DC-based system might make most sense.) Expeditions that are less connected to fuel supplies and are thus more self-sufficient (renewable generation, energy storage) and/or have more minimal load requirements might be best constructed as DC microgrids.

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Application #6—Data Center Support Systems

Data centers contain complex electrical systems that power computing equipment and the supporting infrastructure systems. Although the critical energy end use in data centers is the computational (IT) equipment, the infrastructure systems' energy end uses (HVAC, power distribution and Uninterruptible Power Supplies, standby generation, lighting, communications, etc.) also consume a large amount of energy. [1]. It has been reported [2] that the electrical efficiency of data centers can be as low as 30%. One efficiency measure evaluated recently is to convert the power architecture from AC to DC systems [3, 4]. Many studies have shown that Data centers distributing DC to the IT equipment eliminates several electrical power conversions resulting in lower electrical power losses than their AC counterparts [2, 5, and 6]. This also results in lower energy use for the HVAC systems since the power losses create additional heat that must be removed.

The main subsystems/loads in Data centers are [2]:

- ✓ IT loads/equipment (Servers, networking devices, storage systems). Within IT equipment, energy use includes power supply conversion losses.
- ✓ HVAC (e.g. Fans, Pumps, Compressor based equipment)
- ✓ Power distribution devices (UPS, PDU, Transformers, Wiring, Switchgear.)
- ✓ Backup generators (Heater and Controls losses)
- ✓ Lighting,

Energy Efficiency

The comparison study here will consider the energy efficiency improvements if the entire data center is converted to operate with DC systems. It should be noted that modern state of the art data centers can have Power Usage Effectiveness (PUE) values closer to 1 (several examples of PUE of 1.2 or less) and in most case less than 2. Power usage effectiveness is defined as [7]:

$$PUE = \frac{Total\ energy\ use\ of\ the\ data\ center}{IT\ equipment\ energy\ use}$$

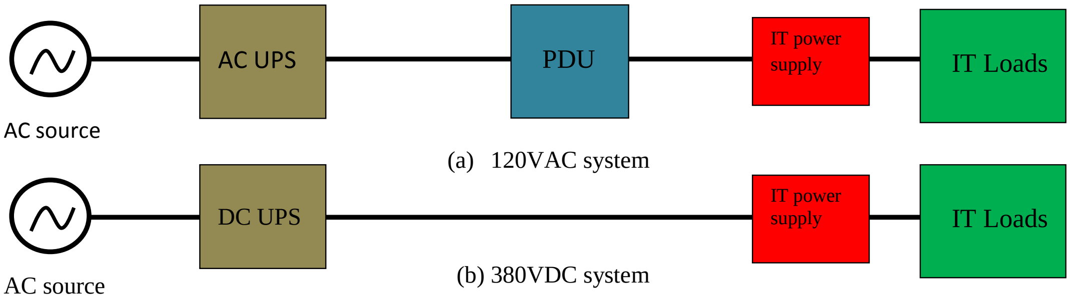
Typical data centers have PUE values in the range of 1.8 to 2.0. Legacy data centers can have PUE values of 2.5[1] or greater. A PUE of 2 means that for every kilowatt-hour consumed by IT equipment, there is one kilowatt-hour consumed by other infrastructure systems. While today's data centers are often designed to have relatively lower PUE values (less than 1.2 in some cases), it is important to focus on both IT and infrastructure energy use. In data centers (even with low PUE values), conversion of infrastructure systems as well as IT equipment to operate on DC would result in additional savings. However in these types of centers the relative percentage of savings would be less than from a traditional data center with higher PUE values.

The study of two different AC and DC systems [6] is considered here. It has been shown that the components in the DC system are superior or at least equal to their AC counterparts in terms of energy efficiency. In particular, in an AC distribution system, UPS systems provide uninterrupted power to the IT equipment and sometimes to other infrastructure systems. The UPS systems first convert AC to DC and charge batteries. Then another conversion restores the DC back to AC. Both power conversions consume some of the energy and create heat. The AC is then distributed to the IT equipment. This distribution may involve power distribution units that contain transformers transforming one AC voltage to another (e.g. 480V to 208V). This conversion also consumes energy and creates heat. Finally, inside the IT equipment, AC power is converted to DC power further losing energy and creating heat inside the IT equipment. All of the power conversions create heat that then drives the need for additional HVAC energy use. The DC voltage at this point is 380V.

In DC distribution, a conversion from AC (typically 480VAC) to 380V DC takes place (or slightly higher to account for other losses). Batteries are charged, but there is no need for conversion back to AC. The DC power is delivered to the IT equipment where a conversion from AC to DC in the power supply is not necessary. For this reason, DC UPS efficiency can be greater than the AC counterpart, other distribution conversions are eliminated, and there is additional conversion loss savings within the IT equipment. All of these savings also reduce the HVAC load in the data center.

Previous studies and demonstrations have focused on the power chain to the IT equipment. In a truly DC powered data center, the infrastructure systems could also operate with DC. This includes lighting, DC motors and drives, communications, etc. These systems similarly have native DC as the end use, and elimination of unnecessary power conversions would further reduce loads and less heat would need to be removed. There is no published data on efficiency gains for DC powering of infrastructure systems, however, similar efficiency gains as in the distribution to IT equipment are expected. In addition, DC powered equipment (e.g. LED lighting, electrically commutated DC motors, etc.) is more efficient than their AC counterparts.

DC UPSs efficiency can be comparable or better than AC UPSs, the 208/120 VAC requires extra conversion, and there will be a need for Power Distribution Unit (PDU) transformers (that causes about 4-7% of the total losses in standard transformers and about 1-3% in premium transforms [1] according to the loading conditions). The power supply of IT loads in DC systems is more efficient than its counterpart, since the first stage conversion in the power source can be eliminated and this make it 2% more efficient compared to AC power sources. In addition, less cooling is required if these transformers are eliminated from the system (elimination of heat produced by these transformers, decrease in the space required in the data center, lower capital and installation cost, fewer points of potential failure). For the purposes of this study, we are comparing the two following systems: 380 VDC system, and 120VAC system. These two systems are shown in the figure below:



(a) 120VAC system

(b) 380VDC system

If we neglect any losses before the UPSs since those are common in both systems, the losses in the first system will be caused by the AC UPS, the PDU, the IT power supply, and the wiring losses. On the other side, the losses in the second system will come from the DC UPS, the IT power supply, and the wiring losses only. From the first glance, it can be concluded that the extra conversion steps in the AC system will cause more losses in the AC system. The following table shows the efficiency comparison between the two systems, the efficiency values in the table were calculated with numbers collected from different sources as shown and they considered that the loading of each system goes from 10-40%. It should be noted that the AC system devices considered here are modern devices while some comparison studies use less efficient AC devices to be compared with modern DC devices, which leads to a misperception of the actual efficiency values.

	UPS	Wiring	PDU	IT power supply	Overall
AC system	88-96.20%[8]	98.50-99.00[10]%	97.93-98.15%[1]	90.00%	76.39-84.12%
DC system	97.10-98.00%[9]	98.50-99.00%	N/A	91.75%	87.75-89.01%

It should be noted that the UPSs efficiency values depend on the conversion technique (Double or delta conversion) and the kVA ratings of the systems. The UPS data in the table is taken for a UPS with delta conversion with 1 MVA ratings. While the PDUs efficiency values depend on the transformer type, it should be noted that the PDU efficiency losses depend on the system hierarchy since some systems will require that multiple PDUs are used. In the above calculations, only one PDU is considered. .The above results illustrate the fact that eliminating the power electronic conversion stages will increase the system efficiency. On the other hand, it is to be noted that the wiring loss numbers are identical for both systems because the loading condition is chosen to be between 10-40%. If the wires in both systems are loaded to almost their rated capacity, the losses in the AC part will increase significantly [12]. Another major benefit for DC systems in data centers is that they require 33% less floor space compared to AC [4], and require less cooling in the data center, and hence, saving in capital, construction, and maintenance will be achieved.

Reliability

Besides higher efficiency levels, DC systems are found to be more reliable (in part because there are fewer potential failure points); a study by Nippon Telegraph and Telephone (NTT) was done for 10,000 AC UPS and 23,000 DC systems between 1996 and 2004. The field data showed that the unavailability of the AC system was in the range between 10^{-7} and 10^{-8}, while the DC systems showed no failure for all years under study except for 1999 where the unavailability was 10^{-9} [13]. In [4], the authors presented a calculated reliability comparison that shows higher improvements in DC system reliability. The reliability of 380 VDC with regulated bus availability was 0.999998 with 200% improvement compared to 208 VAC systems, while the 380 VDC with direct connect to battery bus availability was 0.9999996 with 1000% improvement.

Wiring Costs Comparison:

To compare the electrical wires costs between the above two systems, we consider the following cases [6]:

a) For the 400/280 VAC system if we consider a 50 Amp wire, for a 3 phase with a neutral system the power delivered will be 34.6 kW with 8.65 kW per wire.
b) For the 380 VDC system if we consider a 50 Amp wire, for a 2 wire system the power delivered will be 19 kW with 9.5 kW per wire.

If we compared the above two results, we can conclude that the copper reduction in DC systems is about 10%. However, it should be noted that neutral wires for AC systems must be oversized for harmonics considerations based on the harmonics contents in the system. The AC system neutral wire size may be required to be increased according to the third harmonic percentage in the system [14]. For example, if the third harmonic contents in the system are 20%, the neutral wire must be oversized for the upper size available.(change from 16 mm^2 to 25 mm^2 for example)

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Application #7—Coupling a DC Microgrid to a HVDC Line

Introduction

Significant amounts of research is being conducted to enable direct current (DC) microgrids. For non-islanded applications connections to local distribution, transmission, or microgrid networks becomes an important consideration that impacts power quality and availability for microgrid loads. This section focuses on high voltage DC (HVDC) interfaces of DC microgrids to other systems. For this discussion DC voltage ranges are defined according to the International Electrotechnical Commission (IEC) [4].

- High: > 1500 V
- Low: 120V – 1500 V
- Extra low: < 120

Historically the majority of electric power transmission and distribution systems have been alternating current (AC) because of the simplicity associated with transforming and transmission of AC power. However, there are a number of advantages associated with HVDC transmission when the distances are long. These include reduced conductor per unit length and no skin effects which equate to lower capital costs and lower losses [2]. Loss reduction for this long distance transmission ranges from 33.3% to 76% [3].

DC transmission was first demonstrated in 1882 at Miesbach-Munich Power Transmission [2] and first used in a commercial transmission system developed in the late 19th century by Thomas Edison [5]. Technology development for HVDC was extensively pursued in the 1930s by the General Swedish Electric Company (ASEA) and followed by early commercial installations in the 1950s [2].

Today DC power and DC coupling are used for more than long distance cost and efficiency gains. Independent AC power systems can be interconnected without the complication of matching voltage frequency and phase. Transients in one power system can be isolated from generation and load in another power system improving power quality and overall system resiliency. Improved matching to energy storage by eliminating AC/DC and DC/AC conversions is also leveraged but DC/DC conversion is still typically used for power flow control. In addition, losses associated with water in submerged applications often prevent the use of AC power.

Many countries have invested in HVDC interconnections. Examples include:

1. Moscow to Kahira connection in the Soviet Union, 1951 [2]
2. Gotland to mainland Sweden 100 kV, 20 MW system, 1954 [2]
3. Xiangjiaba to Shanghai connection in the China 2,071 km (1,287 mi), ±800 kV, 6400 MW link [2]
4. Porto Velho to Rondonia, Rio Madeira link in Brazil, [2,3]
5. Baltic Cable, undersea between Sweden and Germany [2]
6. NorEd cable, undersea between Norway and the Netherlands [2]

7. Basslink, undersea between Tasmania and mainland Australia [2]
8. Nelson River DC transmission system in Canada [2]
9. Tres Amigas SuperStation project connecting the Western Interconnection, Eastern Interconnection, and ERCOT for controlled power sharing across North America. [7]
10. English channel interconnection between England and France [2]

China continues to make significant investments in HVDC connections and is on a path to have the largest capacity of DC transmission in comparison to other countries [10].

As microgrids become more prominent in usage and include connections to distribution lines, transmission lines, and other microgrids additional advantages of the interconnections will be leveraged. Improved utility performance through isolation of stochastic renewable sources and loads in microgrids is achievable through proper control design of the coupling. This can result in the virtual creation of more ideal generation and load behaviors. Other ancillary services such as voltage regulation for the larger utility are also possible. Research in these areas often focuses on the controls [9, 12] and converter topologies [11].

Metrics

Safety and Protection

As with any DC system protection can be complex in comparison to AC systems. The challenge with DC systems is often disruption of fault currents. In AC systems the zero crossings in the current shape allow for arcs to be extinguished and not reclose. Techniques for disrupting DC currents often involve methods such as using magnetic fields to stretch and break the arcs.

Utilities that own HVDC transmission have been operating with this challenge for many decades. However, as HV converter technologies become more semiconductor based safety and protection will be an ongoing challenge that must be addressed.

An equally important but somewhat opposite concern regarding the safe design of microgrids connected to the utility or other microgrids is achieving large enough fault currents to activate circuit protection. As an example fuses have a time response that shortens as the currents reach higher amplitudes. If a microgrid is dependent upon the utility to provide some of this fault current to activate the circuit protection the surge capability of the HVDC coupling will become important.

So, safe operation of HVDC components and systems have been successfully performed by utilities for many years but as microgrids become the load on the down side of these coupling points the approach and likely the complexity associated with designing a safe system will change and must be addressed in future research.

Reliability

When considering the reliability of a system it can be helpful to think of probability of an event and the consequences resulting from that event. In this section high reliability would imply a high probability of an event occurring but low consequences as a result.

When considering consequences the total loss of energy in a power system, for the purposes here, would be considered a high consequence event. Therefore if a power system relied on a single energy source the consequences associated with losing that source would be high. The number of sources increases for a DC microgrid when it is connected to a utility distribution line, utility transmission line, or a network of microgrids. This has two results. First, the likelihood for a total loss of generation for a microgrid would decrease because of the increase to the number of potential energy sources. This allows a greater ability to source critical loads during a partial loss of generation and thereby reduce the consequence associated with that loss. Second, as the number of sources for a microgrid increases the probability that one of them will fail will increase but as already stated the consequences should be lower. For these reasons the reliability of the microgrid would expected to be increase. This is also true for the utility or network of microgrids that the DC microgrid is connected to if the DC microgrid can also share power.

When considering the reliability of HVDC interface hardware between the DC microgrid and an external power system comparisons can be made between

- the HVDC DC/DC link and a high voltage AC/DC link and
- the HVDC DC/DC link and a high voltage AC/AC transformer.

In simplest form a basic buck-boost DC/DC converter would have one active and three passive components [6]. A basic bidirectional three phase AC/DC converter would have six active and eight passive components [6]. For either converter a loss of a component would result a nonoperational state. The AC/DC converter could potentially service two of the three phases for AC to DC energy flow but overall power quality would be expected to decrease.

Parallel DC/DC converters could be constructed with fewer components than required for one AC/DC converter. In this configuration the loss of one DC/DC converter component would still allow power sharing and therefore be a configuration that would increase the overall reliability of the system.

When using a DC/DC link or even an AC/DC link rather than an AC/AC conventional transformer the reliability of the interface is expected to decrease. This is because conventional transformer technology does not have active components, has few components, and is a very robust technology. However, this needs to be weighed against other services that an active link can provide. Active interfaces can provide an additional level of isolation between power systems in addition to other ancillary services such as increased power quality through power conditioning. For DC/DC links this power conditioning can be simpler to implement due to lack of frequency requirements.

For power electronic based converters many of these active components require a series connection of many active components to reach the voltage hold off needs or a parallel connection of many active components to reach the peak current needs. Research in improved thermal management and advanced materials such as wide band gap semiconductors continues to address these issues. Enabling reductions in the required numbers of components will enable a greater amount of redundancy in converter designs resulting in higher reliability.

Capital Cost

Capital costs for DC converters can be significant. For example cost estimates for HVDC converter station equipment capable of 2000 MW, 500 kV bipolar DC link between England and France is estimated to be $173.7 M [2]. This equates to about $87k per MW.

Technology advancements will continue to bring these costs down. Examples include:

- Improved thermal management through technologies such as the Sandia Cooler [8] which increases the heat transfer per unit surface by a factor of ten over conventional air cooled heat exchangers.
- Increased junction voltage enabled through ultra wide band gap semiconductor material research. High voltage devices enabled by materials such as GaN would reduce component count and therefore converter complexity and costs. Sandia National Laboratories is presently pursuing the development of these materials to enable device manufacturing with reduced defects.

Efficiency

A number of factors impact the coupling efficiency between a DC microgrid and a HVDC line. To control power flow and enable step changes in voltages DC to DC converters are utilized. This introduces a number of complexities and loss mechanisms that would not necessarily be found in an AC voltage transformation. These include:

- Semiconductors losses and
- Passive component losses.

These losses are driven by the types of materials, design of the converter, and the ratio of the HVDC line voltage to the microgrid bus voltage [6] (chapter 7 buck-boost converter).

Corona discharge can also impact efficiency. Losses associated with the formation and oscillation of ions around high voltage components and cables is an effect that is less of an issue for DC systems [2].

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Application #8—Electric Vehicles for Backup/Emergency Power

With recent natural disasters, policy makers and Federal, State and local agencies have become interested in "Shelter-In-Place" approaches that allow citizens to stay located in buildings. Electric and Plug-In Electric Vehicles (EVs & PHEVs) are considered one potential very useful component to offer backup, emergency power to buildings and microgrids that would enable the "Shelter-In-Place" strategy.

With regard to DC microgrids, this application investigates if associating the batteries of EVs and PHEVs that operate at 350 Vdc to a DC microgrid offer any advantages along the metrics outlined in this report.

The results presented in Application #1 are also valid for Application #8. The difference between the two applications is the addition of Plug-In Electric Vehicles (PHEVs) and Electric Vehicles (EVs). From an efficiency point of view, and not focusing on any resiliency or other considerations, EVs can be modeled as batteries and PHEV can be modeled as batteries and generators. If we assume that the AC/DC converters have a similar efficiency to the DC/DC converters, then adding some batteries in the microgrids of Application #1 and focusing on the comparison between the AC and the DC microgrid, should lead to different results than the ones described in Application #1. Given however, that the EV and PHEV batteries operate in the range 300-400 Vdc, a DC/DC converter might not be necessary in the DC microgrid case, leading to higher efficiency gains for DC microgrids.

Certainly, however, if DC/DC converters are less expensive than AC/DC converters, a high number of EVs will result in lower capital costs for the DC microgrid in comparison with its AC counterpart.