The Need for Communications to Enable DC Power to be Successful

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Abstract— **Alternating Current (AC) is the most common form of power available within buildings. This has historical reasons rooted in large-scale utility generation and distribution of power. With the rapid emergence of local renewables (notably solar) in buildings, the availability of Direct Current (DC) power is becoming more prevalent. In this position paper, we argue that managed power distribution of DC is possible with the addition of communications *about* power. We claim that with communications DC power distribution becomes much more efficient and effective than with no communication, and provides other benefits. The Local Power Distribution (LPD) model is described where commodity interfaces enable a "plug and play" approach to operating DC power sources, batteries, and loads within a building. We seek a future where communications coupled with DC power distribution, storage, and use can create buildings that are more efficient and easier to operate.**

Keywords—microgrid, nanogrid, power distribution, DC power.

I. INTRODUCTION

A century ago, in the "battle of the systems", Alternating Current (AC) bested Direct Current (DC), principally for the ease of dramatically changing voltage up and down with transformers [1] to enable efficient distribution of power over long distances. For many applications, DC has benefits, and in the absence of AC's historical position, might otherwise be the better choice. The question then is, what set of circumstances could lead to a different distribution of usage between the two technologies – AC and DC – at least for use in buildings – to enable the most efficient and effective use of power. This paper argues that communications – specifically, *communications about power* – is essential to making DC much more widely used, and so more "successful".

The rest of the paper is organized as follows. Section II reviews the difficulties presented for DC given the current dominance of AC. Section III identifies many specific features that are greatly improved with communications, or not possible at all otherwise. Section IV outlines how these features collectively can provide an attractive rationale for adoption, and a path for wide deployment of DC power. Section VI provides a summary and briefly describes future work.

II. CHALLENGES OF AC'S INCUMBENCY

The global fraction of electricity use that is AC is overwhelming. In the early development of electricity distribution systems, AC had several advantages, most notably the ease of dramatically changing voltage levels to attain needed efficiencies in transmitting power over long distances. With utility distribution being AC, it was natural for end-use devices to also be AC, even if they could be DC just as easily (for example, incandescent lights and motors), or were natively DC (for example, all forms of electronics, fluorescent lighting, and LED lighting). In industrialized countries, AC power is available in nearly every room of most buildings, and for end-use devices, has "plug-and-play" ease of use. While DC alternatives have been long available, they have typically been used only for niche applications, such as rail transport, and appliances for recreational vehicles. As AC products are sold in much larger quantities, they are usually less expensive and much more available than their DC counterparts. Use of DC is slowly growing, but still mostly for new specialized applications such as wireless access points, telephones, and small portable devices with internal batteries that need to be charged. Building trades and local code enforcement officials have much more familiarity with AC. There is confidence that parts for AC systems will be available for the long-term. While AC wall outlets that include USB ports have been available for a number of years, they are only DC at the actual outlet and so do not gain efficiency advantages from avoiding AC/DC conversions, and nearly all of these were produced before USB dramatically increased its available power per port with the USB-PD specification [2].

While renewable generation usually starts out as DC, it is ultimately almost all converted to AC – with significant losses from the conversion – for integration with the utility grid. Within buildings, there are small uses of DC in Power over Ethernet, in telecom facilities and in a few data centers. Vehicles are the largest use of DC, both the electrical systems in conventional vehicles, and in the power trains of hybrid and fully electric models. The use of High-Voltage DC (HVDC) for long-range grid transmission of electricity is not in scope for this paper as it does not take place within or between buildings.

It is not feasible (nor likely desirable) to convert all usage in buildings to DC, as the advantages of grid distribution of AC power still seem insurmountable (excepting HVDC). In addition, except in niche applications (for example, data centers), use of *only* DC even within a single building is not merited, particularly as building owners will want to make continuing use of their existing AC equipment and appliances. Thus, adding DC requires new devices to interface with the AC system, new wiring, and new end-use devices. This is done today, but its complexity and cost are high barriers to overcome.

DC has been used without communications for well over a century, including for rail transport (streetcars, subways, and inter-city), in motor vehicles, telecommunications facilities, and more recently in data centers. These are all specialized applications, and except for vehicles, highly managed. The emergence of the 380V DC standard will be an asset in this regard, for its higher efficiency and so ultimately lower cost than traditional low-voltage DC (<60V) or proprietary higher-voltage technologies. Today it is likely that the total end-use distribution of DC is less than 1% of electricity use in residential and commercial buildings, and certainly well under 5%. If DC were to be more "successful", it would cover a much larger fraction of electricity consumption. How might this occur? Greater use of DC will require it to be adopted in many buildings it is not used in today, for new end uses, and to displace existing AC loads rather than add new DC loads (as with IP cameras or wireless access points).

III. TWO PATHS FORWARD

We can consider two paths to making DC successful – with, and without, communications. The first path would use the DC technologies already in wide use, notably 12V and 24V as in vehicles, 48V as in telecommunications facilities, and the new Emerge [3] technologies of 24V and 380V DC.

Technologies which are defined by open standards and which products are widely available for are called "Standard DC" [4].

> A method for transmitting dc power defined by a well-known technology standard, enabling plug-and-play interoperability.

Standard DC technologies that include communications for managing power distribution within the power cable (over the power wires or over adjacent wires) already exist.

The other possible path is to combine DC power with *communications about the power* on the same cable. This is currently available through at least three standard technologies: USB, Ethernet, and HDBaseT [5, 6, 7]. This combination is called "Managed DC" [8].

> 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.

All are either at or on their way to being able to deliver 100 W per cable. A fourth managed DC standard, UPAMD [9], has been approved by IEEE, but its prospects for being successful in the market have been seriously diminished by the appearance of the USB-PD specification, which provides the same power levels that UPAMD was created to address. There are also proprietary standards that combine communications with power; examples include Redwood Systems (now CommScope), VoltServer, and LumenCache.

The combination of communication with power distribution, storage, and use enables several features not available otherwise, such as covered by Local Power Distribution based on Nanogrids [10][11][12]. Major such features are as follows:

A. *"Plug-and-play" operation for end-use devices*

In existing Managed DC, power is only delivered (other than a trickle amount to enable communications) after each side of a link has communicated to the other about its capabilities and preferences. This allows for customization and optimization of the link, such as by adjusting the voltage to the highest that can be provided, can be used, and is appropriate to the cable, including determination of its capacity and length. In USB-PD, for example, the cable itself reports its characteristics to the devices, and there are a variety of combinations of voltage and current that electricity providing devices and consuming devices can support. Thus, the most efficient combination that both devices can use can be selected.

B. *Improving safety of power use*

By communicating first, conditions which would otherwise be unsafe can be minimized or avoided. If a cable is cut, or not properly connected, this will generally be detected by an interruption in the communication, when can then be used to terminate power delivery, or not initiate it in the first place. Capacity and voltage limitations of the cable or either device can also be respected automatically. AC power systems accomplish some of this to a limited degree through the use of different mechanical plug designs for different voltages and maximum currents. Detection of hazards such as cable overheating are possible through temperature sensors, or through the end-devices comparing the supplied and received power levels, and recognizing a problem when the difference between these exceeds a threshold.

C. *Fine-grained management of constrained supply*

Any electrical circuit has a maximum current or power level that can be supported, due to wire sizes or other component capacities. In conventional AC systems, circuit breakers are used to cut power to all downstream devices when this level is reached. Since this is at best an awkward way to operate, a usual approach is to oversize wires and circuits so that this occurs only rarely. This is wasteful of material (notably, of copper). With communications, actual capacity used can be tracked on an ongoing basis, for what devices can potentially use at maximum, and for what they are actually consuming at any particular moment. Devices can be required to request authority for capacity increases before actually using it, or have such authority revoked. In emergency situations, devices can be summarily disconnected on an individual basis (for star topology deployments at least) when needed. Fine-grained management can both reduce copper and other installation needs and affect the minimum number of devices (and the least important ones) when power limits are reached.

D. *Plug-and-play operation for generation*

A traditional approach to electricity generation is to have generators of variable capacity that can follow the amount of demand and so keep supply and demand in balance. In a system that has more than one generator, including local generation while connected to a utility grid, communications can help determine how much power to generate at any given time, including whether to generate any at all. How best to use diverse generation resources requires consideration of many factors, such as non-dispatchability of many renewables, part-load efficiencies, minimum times to be on or off, cycling losses, and conversion losses between AC and DC and between different voltages. Communications enables these factors to be coordinated in a way that maximizes efficiency and equipment utilization, and improves reliability and safety.

Communication can ensure that a generation resource can safely deliver the amount and type of power it will produce, before it does so. In the absence of this, careful system design and management, as well as additional hardware, are needed to ensure safe operation. Optimal operation is simply not possible without some communications.

E. *Plug-and-play operation for storage*

Electricity storage as a general-purpose tool is relatively new to electricity systems. Existing use of storage has been for reliable or disconnected operation of individual devices ("picogrids" [13]), or in Uninterruptible Power Supply (UPS) systems, where the battery is only ever used when primary supply is lost, and then used to supply all demand.

In the absence of communications, a storage system will generally not know if it should be charging or discharging (or neither), and at what rate. Voltage levels can be used to communicate this, but this is not always reliable. In more complex systems, such as with multiple local generation and multiple local storage entities, communications is needed for proper, efficient, and economic coordination of electricity storage.

F. *Enabling optimal operation with a local price*

Central to the definition of a nanogrid is the presence of a local price that can correctly indicate the relative scarcity of power and so drive efficient operation of end-use devices, local generation, local storage, and exchange of power with a utility grid (if present). As noted above, voltage levels can be used as a first-order indicator of scarcity, but this is not accurate, and does not allow for a forecast of future prices, which has great value in such systems.

Another capability that communications enables is the ability to know when it is advantageous to switch the direction of power flow. Some technologies allow for this today (USB-PD, UPAMD, and HDBaseT); others could accomplish this with two parallel links, one for each direction of power flow. As more cars and other vehicles become electrified, and so may want to be charged from a building, or provide power to a building (whether from their storage or generation), there is the question of which direction power should flow, when, and for how long. Communications can enable this to be easily determined. Without it, manual means are needed to direct power exchange. We can also expect vehicles to be able to be connected to each other, so that one can charge another. Communications with and within vehicles about power should use the same technology as other communications about power.

G. *New powering models*

Conventionally, end-use devices were only ever connected to a single power source (other than a possible internal battery). Exceptions, such as electronic devices in data centers or telecom facilities, are rare. However, Managed DC creates the possibility of devices being easily able to acquire power from more than one source, at different times, or at the same time. This is particularly useful when resiliency is of concern as a device can be powered through one means most of the time, but another means when the first is significantly impaired. For example, it would be convenient if refrigerators could take in DC power from a vehicle or local generation or storage during times when the utility grid is down, or expensive, and use grid AC power otherwise.

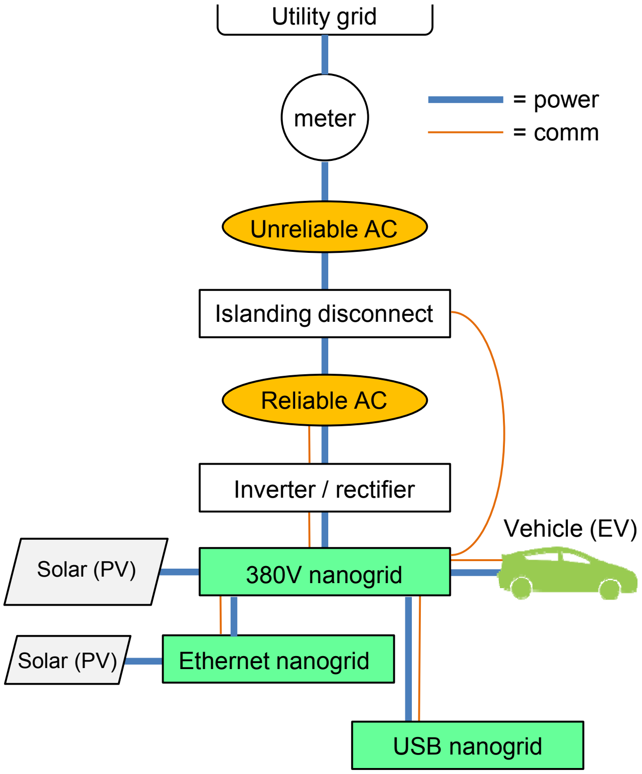
While AC circuits are usually "multi-drop", with many devices possible to attach to a single wire, DC topologies more commonly provide only a single device per power port. This ensures that capacity limits on the cable, and cable length, are not exceeded. However, with communications, we can foresee enabling "multi-drop" capability for technologies like Ethernet [14], which could have significant cost advantages for many devices, including lighting. Unpowered USB hubs provide multi-drop capability, though usually with only modest power levels; the higher-power USB-PD specification will likely be used mostly or entirely with powered USB hubs (and a powered USB hub creates its own nanogrid).

At present, the emerging 380V DC standard lacks any mechanism for communicating about power. A good option to remedy this is to use standard Ethernet links, in parallel to each power link. This could be used without power, or be used for small amounts of power (relative to what the 380V path could provide) to energize the end-use device for communications to negotiate aspects of the 380V line before it is energized, to increase safety.

IV. DC POWER AS A COMPELLING VALUE PROPOSITION

When we consider how changes are made to systems and technologies over time, new alternatives are successful generally not because they are marginally better than the incumbent, but rather because the new choice provides capabilities or efficiencies not possible (or not possible at reasonable cost) previously. DC power has efficiency advantages compared to AC in many applications.. "Direct DC" – use of DC power from local generation or storage in its natural DC form – has efficiency benefits [15], but by itself this is generally not a sufficiently large benefit to drive substantial change.

For consumers, building owners, or product manufacturers to decide to include and use DC power in products, functional advantages not possible with AC can drive much higher rates of adoption. This can put the value proposition over a tipping point to lead people to make changes in product adoption and usage patterns. This has been the case already for recent adoption of DC power in several very specific applications. For example, the rapid spread of charging mobile devices with USB cables is principally due to advantages this has in up-front cost, size, convenience, and portability. Devices don't need a dedicated, non-standard, external power supply that is



Buildings may have several Ethernet, USB, and 380V nanogrids. Nanogrids may contain storage (batteries)

Fig. 1. An example network of nanogrids

(relatively) expensive, duplicative, and inconvenient. Recently Apple Computer announced that future MacAir models will be powered through USB-PD [16] and so not require a product-specific supply. Data centers are adopting DC for efficiency benefits, but also for reliability and capital cost advantages over AC alternatives. Ethernet for phones and access points is used for the lower cost and difficulty of installing wiring.

Recently we have seen a significant increase in interest in reliability and resiliency, particularly for electricity supply. There is increasing recognition that central power systems such as the utility grid have inherent vulnerabilities in the face of natural disasters, random equipment and power line failure, as well as from cyberattacks and other human-caused disruption. Local power, which is easier to accomplish with DC, has a clear opening here to improve power reliability. In addition, with the most basic function of any grid to balance supply and demand, communications offers mechanisms to do this better than otherwise.

We argue that there are three plausible directions to consider for the combination of communications and DC power; they are:

A. Applying technologies from the utility grid and very large building management domain; these generally communicate with legacy protocols such as SCADA, MODBUS, and BACnet—and are then adapted to create systems of managing DC microgrids. An AC-based example of this approach is the recent "Coalition of the Willing" effort [17] for utility microgrids.

B. Using the set of technologies we have today for managing power distribution across a single link, as-is, as with Ethernet, USB, and similar technologies.

C. Adopt the Local Power Distribution (LPD) model to create a network model of power, and organize power distribution bottom-up, starting with individual devices.

Direction A is guaranteed to be very expensive to design, purchase, install, and maintain, as these types of systems are highly complex and require significant custom and manual procedures. Direction B is widely available and low-cost, but being only for low-power capacities and only for single edge links, has severe limits in what it can accomplish. Direction C is based on creating commodity interfaces and products, with plug-and-play capability, so is intended to be low-cost to buy and deploy, and should require minimum design cost, and be easy to maintain. As the technology gets wide use, the capacity of individual links can be scaled up much as has occurred with many communications technologies. The goal of LPD is to eventually bring 100% of electrical devices in buildings into a common communications paradigm for power distribution.

It appears that Direction C is the only one of these that can make DC widely successful. The first step in doing this would be to add several capabilities to Ethernet and USB to enable distributing prices (and forecasts) to end-use devices. For example, doing this for Ethernet for an instantaneous price would only require defining a single TLV variable [10] that is then transmitted across the link with the Link Layer Discovery Protocol (LLDP) [18]. With modest standards development, new devices could gain LPD capabilities even without new hardware development.

To add DC devices to buildings in the form of nanogrids as envisioned by LPD can be done incrementally and organically. Many buildings today already have USB hubs and devices. Ethernet-powered devices are numerous, but in fewer buildings. Nanogrid controllers for Ethernet and USB devices could be added to buildings as end-use devices are installed that can use them. As more DC devices are purchased, the nanogrid controllers can be replaced with larger ones in the same way that Ethernet switches can be readily replaced and moved as needs dictate. Some of these controllers will have the ability to directly accept PV power as an input, in addition to grid power. Many will incorporate internal batteries to provide reliability in the face of grid outage, and to use for economic advantage when grid tariffs become time-varying.

Fig. 1 shows an example deployment in a building of several nanogrids. In the figure, the several distinct domains of power are shown, either from different voltages (with the DC nanogrids), or different reliabilities (as with the AC ones). End-use devices are not shown in this figure – they are part of the nanogrid domains.

A system may start with – or may already have – Ethernet and USB supply devices that are currently AC-powered. A 380V nanogrid controller may then be installed which can supply higher power devices, and directly interface to on-site PV generation as well as to vehicles – the latter for power flow in either direction. The 380V controller is highly likely to have an internal battery. Additional Ethernet and USB nanogrids may be added, with all eventually powered from the 380V controller rather than from AC power. Many of these grids may also have internal storage, and the ability to connect to local generation.

Over time, nanogrids can be networked to each other, to more local generation, and to vehicles. A common configuration is likely to be to have most or all devices that are deemed critical for reliability to be in a DC nanogrid; a few AC devices that are important could be put into a subsection of the AC infrastructure that is islanded when the utility grid goes down. The local price model could be extended to select AC devices. The inverter/rectifier device can also include a nanogrid controller for the AC reliable grid. The amount of support for reliable AC could be kept small and so not impose a large cost burden on the infrastructure needed for it. Since the components of this system would all be commodity products and often modular, the cost for purchasing, installing, and maintaining such systems should be much less than an AC counterpart. As needs change and technologies evolve, the system could similarly be changed out in its hardware and software components, much as is done with IT infrastructure.

V. SUMMARY AND FUTURE WORK

Local renewables are rapidly increasing the amount of DC power that is available within buildings. To most efficiently use this generated power, it should remain in its DC form and not be converted to AC (and then potentially back to DC again in the case of electronics) with resulting power losses. The same issues apply to local electricity storage. Beyond efficiency gains, the use of locally generated DC can enable greater reliability and safety of power use. To enable these benefits – that is, to the create the compelling "DC value proposition" – we have argued that communications about power is needed. There are several paths for achieving communications about power – we argued that the LPD model based on nanogrids is the only path available with much promise. We seek to ensure that DC technologies have communications capabilities to provide more and better value to consumers and building owners.

Future work will be to define the technology building blocks necessary to economically add communications to DC power distribution. We argue that these building blocks must be standardized and that the LPD model provides a roadmap on how to do this.

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