

DC Local Power Distribution with Microgrids and Nanogrids

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Abstract—Many aspects of our electricity systems are rapidly changing, including the ability to locally generate power with renewable energy sources and integrate local storage. Key factors that led to our current grid architecture may no longer hold in the near future. A new approach to power distribution within buildings is Local Power Distribution (LPD). In LPD individual devices are organized into nanogrids (a single domain of power) with nanogrids networked to each other, to local generation, and to a building-wide microgrid. Nanogrids inherently incorporate DC power for efficiency. This new model for electricity distribution in buildings is implemented with a layered model of power – called Network Power Integration (NPI) – that isolates communication about power from communication for functional purposes.

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

I. INTRODUCTION

What if we had no existing electricity grid—no central generation, transmission and distribution lines, and no end-use devices, utility companies, and power technologies? What technologies and infrastructure would we create knowing what we know today, particularly from our experience with Internet technology? Would the resulting electricity system be similar to the electricity grid of today, or perhaps quite different? This paper argues that electricity distribution would be different in many important respects, notably with much greater use of DC power and vastly more “local grids” (microgrids and nanogrids). We arrived at our present state through a long history, constrained by available technologies, and propelled by inertia. The question is not whether those past decisions were wise, but with today’s knowledge and technology (notably local power generation of DC from solar panels), how should the future be different? The answer should guide energy policies and investment in energy research. In this paper we propose “Local Power Distribution” (LPD) which takes a new approach to power distribution within buildings, organizing it from the bottom-up on a network model, with all end-use devices communicating and intelligent, with autonomous but interconnected “local grids”, and prices local to each domain.

This paper does not address whether or how the structure internal to the utility grid should evolve. It is assumed that it will continue to supply AC power to individual buildings, offering an increasing array of financial options and incentives

to shape electricity flows at the meter to most cost-effectively meet the needs of the grid. The question at hand in this paper is what structure should exist inside of buildings. This discussion is focused on industrialized countries, though the technology directions are even more valuable for developing countries that have yet to invest large quantities of capital in traditional utility grid systems and AC devices.

We address the key question of “how to most *economically* and *fairly utilize* locally generated DC power to balance supply, demand, and storage, in any building context or grid context?” In our key question we define *economically* to encompass both capital and operational expenses, *fairly* to address prioritization of electricity use (to match the quantity and timing of electricity use to the relative and absolute priority of service delivery), and *utilize* to encompass distribution, storage, and use of electricity, including across time.

This paper makes three key contributions to the field of future grids: The requirements for LPD are formally defined; an architecture for LPD based on the nanogrid is described; and LPD is evaluated in the context of existing work. In addition, the Network Power Integration layering model is named and refined.

This rest of this paper is organized as follows: Section II describes recent developments that drive our reassessment of power distribution technology. Section III lists requirements for power distribution technology within buildings. Section IV presents the Local Power Distribution grid architecture. Section V covers why LPD is preferable, particularly as informed by Internet technology. Section VI considers related work. Section VII presents future directions and a summary.

II. PRESENT CONTEXT

In recent years, a variety of trends have shifted the context of our electricity systems substantially from that which existed when our current structures were solidified a century ago. The most significant of these are:

- Local DC generation is readily feasible with PV solar
- Local DC storage is becoming feasible with more efficient and less expensive battery technology
- Devices powered by standard low-voltage DC are increasingly available and valued for convenience

- Many loads are now natively DC (e.g., all electronics, LED lighting, many motors, etc.) and most others could readily be converted to DC
- Conversion between AC and DC requires relatively expensive hardware, adds losses, and reduces reliability
- DC-DC conversion is now efficient and inexpensive
- Mobility and flexibility are increasingly valued
- Entangling devices in buildings with external controls as with the Smart Grid introduces security and privacy concerns and vulnerabilities
- The utility grid is unreliable or non-existent in some parts of the world; it is always unreliable to some degree everywhere
- The desire for local reliability and resiliency is growing with concern about natural or human caused disasters
- It is increasingly likely that most buildings will have local generation, local fixed storage, or an electric vehicle, if not all three

Future electricity distribution systems must operate within this new landscape focused on local generation, distribution, and use. These combined are sufficient for reconsideration of the fundamental architecture of electrical grids.

III. REQUIREMENTS FOR BUILDING POWER DISTRIBUTION

In this section we consider requirements for addressing how to most economically and fairly utilize locally generated DC power. Within an electrical domain (e.g., within a building) we propose the following as key requirements:

- Minimize electricity losses (e.g., from conversion and transmission)
- Minimize capital costs for distribution systems (e.g., inverters, breakers, and wiring, including professional labor) and for devices that use power (e.g., voltage conversion and regulation circuitry)
- Prioritize electricity use among devices to match changing balance between demand and supply, including making best use of storage (balancing electrical efficiency, battery lifetime, economic value, and providing local reliability)
- Allow all devices, including generation and storage, to plug-in to power sockets without manual configuration, central authority, or professional labor
- Maximize resiliency and reliability in face of equipment failure or challenges from natural or human disruptions, and minimize risk from security and privacy exposure
- Easily interconnect electrical domains to economically exchange electricity (e.g. to coordinate balancing utility grid and local grid needs)

IV. LOCAL POWER DISTRIBUTION AS A SOLUTION

This section describes a collection of technologies that fulfills the requirements in section III.

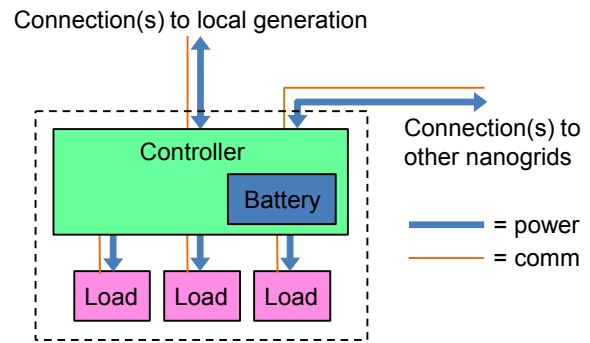


Fig. 1. Schematic of a nanogrid (adapted from [3])

In an LPD future, energy use in buildings is mostly DC in microgrids. Microgrids are principally constructed as a network of local nanogrids, with integral storage, and connected to local generation. Utility grids are much smaller (less capacity, energy flow, and capital requirement), and less reliable. As autonomous DC systems, local grid stability is decoupled from the utility grid. DC nanogrids and DC microgrids cover most end-use devices and most energy use within buildings.

The technology basis of this future state is “Local Power Distribution”—the idea that electricity distribution should be managed from the bottom up—from individual entities and the topologies of their interconnection. In many ways, it is the inverse of the Smart Grid. It presumes digital communication among entities, embraces DC power, and is only intended for use within (or between) buildings. Building-scale microgrids are built on a foundation of nanogrids and pervasive communication.

At the core of LPD is the Nanogrid [1][2][3][4][5], which organizes individual end-use devices into a grid context (see Fig. 1). A nanogrid is a single domain of power—for voltage, capacity, reliability, administration, and price. Nanogrids include storage internally; local generation operates as a special type of nanogrid. A building-scale microgrid can be as simple as a network of nanogrids, without any central entity. A microgrid controller might integrate knowledge of, and control over, the nanogrid entities within it, and can also interface to a utility grid. Utility grids differ across geographies, by voltage, AC frequency and communications technology. Microgrids bear the sole burden of accommodating utility grids and so are specific by location. In contrast, nanogrid interfaces are universal—across any country and any building type or usage context. Nanogrids are indifferent to whether a utility grid is present: always, never, or intermittently. Fig. 2 shows local grid scaling and how it is analogous to that used in Internet Protocol (IP) networks.

The primary way that energy use is prioritized within a local grid is with a local price. A price is a current price and a non-binding price forecast (e.g., for the coming 24 hours). Each grid has its own local price, since the availability of power is different for each local grid, but the price in adjacent grids typically has a strong influence on the price within a grid. Local grids have two modes of operation: normal, in which price is the sole arbiter of operation, and emergency, in which other means (locally determined) are used.

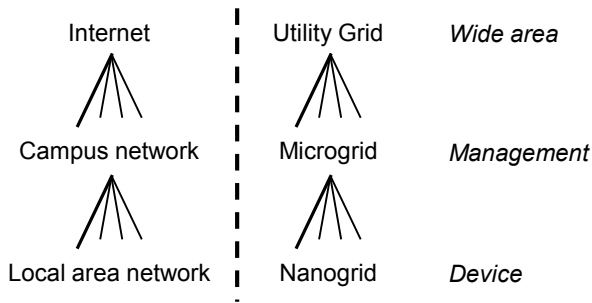


Fig. 2. Scaling structure of communications and power (from [6])

In a nanogrid all loads take the local price into account, along with functional goals from other communications, in determining their operation. Prices are also core to negotiations to exchange power between local grids, and to how a local grid controller manages the storage internal to it.

Local grid connections—nano or micro—are usually internal to a single building (or campus—any single management entity). However, there is no barrier to grid interfaces between buildings. Within a management entity, prices are useful and important, but it is not necessary to track electricity value exchanged. However, between management entities, mechanisms are needed to periodically transfer funds equal to the net value transferred. These mechanisms are out of scope of LPD technology. All connections are peer-to-peer so that energy, value, and communications are only between entities that have a direct wired connection to each other. This dramatically reduces the scope for security risks and privacy intrusions.

Local grids can, on an opt-in basis, incorporate control mechanisms other than price, and visibility beyond peer-to-peer communications. This is usually done in the context of a microgrid. It is most commonly used to make recommendations to changes in wiring topology and local grid policies, but can include direct dynamic control. However, if such a central control entity ceases to function or communicate, the network of nanogrids will still fully function.

The interface at the utility meter is as simple as possible, electrically and for communications. The only information passed down is the utility pricing structure: current and forecast, with possibly a lower purchase price than sales price. The only data passed up is total current consumption. Anything beyond this is an isolated exception, not part of the LPD architecture (e.g., some vehicle charging may merit coordination between the utility grid and an entity within a building). The internal structure within the building is invisible to the wider network and vice-versa. This interface functions as a narrow waist of minimal complexity that isolates the two domains. Having a utility grid connection does not preclude the microgrid or internal nanogrids from having connections to other buildings (and for reliability this is advantageous). LPD minimizes complexity while maximizing functionality and efficiency.

V. HOW LPD MEETS THE REQUIREMENTS

LPD meets the requirements from section III as follows.

A. Minimize electricity losses

Local generation and storage avoid losses from utility transmission and distribution systems. Local DC grids avoid multiple AC/DC conversions which introduce additional losses. DC/DC power conversion has developed rapidly in recent years. A single integrated circuit can convert over 1700 W of power from 380 V to 48 V DC at 98% efficiency [7]. It is now reasonable to distribute DC at one voltage for longer distances, and then drop down to a lower voltage for actual use. “Direct DC” is DC power flowing directly from local generation to end-use devices, possibly via storage, without ever being converted to AC. This has been shown to save about 10% of electricity use in a U.S. residential context [8].

B. Minimize capital costs

A key barrier to greater deployment of local storage and generation is the time and high labor rates required for installing AC systems; they are also costly to maintain, repair, and upgrade. Low-voltage DC systems that are plug-and-play reduce both the amount of time required and the hourly cost of these activities. Because digital power involves communication before power transfer, it is inherently safer than traditional AC power and should require less planning and permitting. Power systems can be easily reconfigured whenever desired. AC devices that use DC internally require extra hardware to convert AC to DC. Native DC devices can be less expensive, smaller, and more convenient.

C. Prioritize electricity use

The local price is used to shape demand to best match the overall system balance. Having the price local to each grid ensures that it can be correct as the availability of and demand for power is local to each grid. Storage systems have diverse behaviors with respect to electrical efficiency, capacity, and lifetime. LPD enables fine-grained management of storage in coordination with demand, supply, and economic value (in the face of dynamic pricing), all the while maintaining local reliability. Each end-use device takes the local price (including the forecast) into account in determining its behavior.

D. No manual configuration

With many communication technologies, anyone can connect and disconnect devices without concern or any manual configuration. Power technologies that do the same exist and the concept can be readily extended to other physical layers of power. While conventional AC needs no configuration for end-use devices, it is complex for generation and storage.

E. Maximize resiliency and reliability

LPD can immediately adapt to any change in wiring or equipment status, including that which is unexpected from natural or human causes. LPD does this optimally, adapting as best it can. LPD has no central entity whose failure will cause others to not operate. By minimizing complexity and communication, the overall potential for exposing the system to security risks is minimized.

F. Easily interconnect electrical domains

Microgrid controllers coordinate with utility grid communications to balance external and internal needs. How they do this is out of scope of LPD. Links between nanogrids

in different buildings are no different from those in the same building.

G. Other characteristics

LPD has many characteristics widely understood to be valuable. Among these that our present electricity system lacks in either fact or degree are as follows:

- Universal—applicable to any usage context
- Scalable—from W to MW of capacity
- Distributed—locally controlled
- Inexpensive—for wide and rapid adoption
- Flexible and open—to changing needs and applications
- Simple—for users and manufacturers

These characteristics should help LPD be quickly successful in the market and ensure good operation. Two other characteristics deserve more extensive examination.

The notion that a less reliable utility grid would be more optimal is not new. Marnay and Lai [9] present how power quality and reliability (PQR) requirements are diverse across building types and devices, so that providing a uniform level of PQR means that many devices get higher PQR than they need—which wastes capital and energy—while others get too little—which results in welfare loss or requires extra hardware. LPD can provide PQR appropriate to individual devices both by segregating devices into local grids of devices with similar PQR needs, and by using price to enable devices to self-sort their relative priority. Our current structure is brittle in that it involves high levels of concentration of facilities (e.g. generation units and transmission lines), and technology (particularly communications that have security vulnerabilities). DC power inherently has fewer power quality issues than does AC power.

Providing adequate electricity to those who have little or none today—“Energy Access”—is a critical issue of our time. While some can be connected to a conventional utility grid, others are unlikely to be able to anytime soon. LPD can provide grid benefits without the need for a connection to a large-scale utility grid. Most people in developing countries spend much more per kWh than those in industrialized countries, and have far less money to spend. Thus, they have much more need to make the best use of every kWh, be particularly responsive to power availability, and share power with neighbors. As with mobile phones, using the same technology as used in industrialized countries can enable LPD to rapidly become inexpensive and widely available—both of which are necessary for large-scale uptake in the energy access context.

VI. RELATED WORK

LPD as an architecture can be better understood in the context of the history and development of electricity and related technology.

A. Insight from electricity history

It is tempting, but inaccurate, to view history and evolution as always proceeding in a single direction on a clear path. Both have repeatedly had cases in which a strong trend in one direction was later countered by an equally strong move in another. Thus, the overwhelming dominance today of both centralized power and AC should not be understood as necessarily permanent or desirable.

Recent years have seen a surge of mention of the “battle of the currents” in the 19th century between Edison for DC and Tesla and Westinghouse for AC. However, the argument was actually a “battle of the systems” [10]. On one side was the system of central generation, long-range transmission, and the “universal” technology of AC. The other side relied on local generation and distribution, usage-specific delivery technologies, and DC. What we are seeing today is a revisiting of the question of the optimal electricity “system”. However, while 120 years ago it was necessary for one to become overwhelmingly dominant, today we could have a hybrid system, with AC used for the utility grid, and (mostly) DC within buildings.

As an example of how history revisits earlier themes, early electricity systems often had special distribution of 600V DC for “traction”—streetcars providing transportation—which made up even a majority of the output of some utilities. For many later decades, transportation was nearly absent from electricity production, particularly in the U.S. Today, we are seeing a dramatic increase of electricity use in cars—albeit in batteries—at similar DC voltages, with projections that we could again see transportation as a large portion of total electricity consumption.

Computing history also provides examples of shifting paradigms. The original dominance of mainframe computers was followed by a several decade long prominence of personal computing, with a recent shift back to central provision of resources with the “cloud”.

B. Electricity grid and Internet parallels

The conceptual similarity between utility grids and the Internet is not new. Analog computers were used to simulate utility grid operation long before digital computers arrived. Many papers have made the grid/Internet analogy, though have drawn diverse conclusions from it.

Some proposals have included the notion of routing electricity [11][12]. Routing data packets makes sense because they are all different. By contrast, electrons are all the same so that it is their timing, quantity, and location that matters, not the identity of any particular power flows [13]. Routing data is usually over long distances and many hops. Electricity exchange can be very local and minimizing hops is preferred, to maximize efficiency.

Modern information networks are loosely coupled to each other, in contrast to the old phone system. The AC utility grid is necessarily a tightly coupled unitary system. LPD enables loose coupling, which has been noted to be advantageous [11][14].

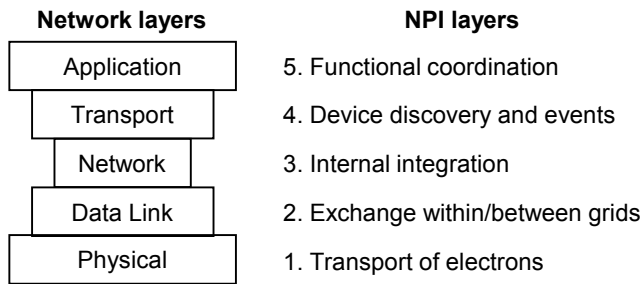


Fig. 3. Layered model for device operation for LPD

The Internet created much more data to exchange than ever passed over the phone system. In contrast, LPD could reduce the amount of electricity that passes over the utility grid. This distinction is due to the fact that information often has little or no locational relevance. Power on the other hand is location relevant in that moving it has costs in efficiency and capital.

For many years, much attention in Internet technology development was given over to research on Quality of Service. Ultimately, increases in capacity and decreases in latency in the Internet infrastructure made most of this obsolete. With advances in storage technology, it is quite possible that most of the concern about how to integrate short-term fluctuations in variable renewable sources may similarly become obsolete. Any complexity introduced for this purpose should be isolated so that it can be later dropped if not needed.

C. Layering

LPD is based on a simple, clear, and effective layering model. Fig. 3 shows layers for IP communication along with our model for power, which we call Network Power Integration (NPI). The NPI model complements IP layering to describe how power concerns are integrated into device operation. Layers 1 and 2 address power distribution. Layers 3 and 4 implement device functionality. All IP data packets flow through the Internet layer, forming the narrow waist, even as they use diverse upper and lower layer protocols. In NPI, no information is exchanged between devices at layer 3; rather, each device integrates its power networking in the lower layers with the functional control networking at upper layers. The device may interact with the same or different groups of devices in the two domains. Devices that functionally interact may be powered the same way, or through different local grids. Devices that are powered the same way may have no functional relationship.

A critical problem with the Smart Grid paradigm is that it lacks a comparable layering structure—one that is simple, clear, and effective. This manifests itself in architectures for managing power distribution and use, which combine mechanisms for power distribution with those for functional control, and treat electricity as a single pool of power for an entire building or region. The most recent and advanced version of this is Transactional Energy [15]. LPD, with NPI, is based on fundamentally different principles.

D. Internet design principles

Principles of Internet architecture are addressed in [16], and while many do not apply to power distribution, the following do. LPD is consistent with these.

- End-points should be primary in implementing functionality, not the interior of the network
- No centralized control
- “Heterogeneity is inevitable”
- Designs must easily scale
- “Keep it simple”
- “Modularity is good. keep things separate”

Robert Kahn identified four “ground rules”: connecting to the Internet should not alter the internal structure of a network; networks should be self-sufficient; communications are “best effort”; and gateways between networks should be kept as simple as possible. LPD is consistent with each of these.

E. Internet history

Many lessons from Internet history [17] apply to LPD. Technology can scale; the first link in the ARPANET was just 50 kbps; links with a million times that capacity are now common. With current digital power standards at about 50W per link, scaling up just a few orders of magnitude covers most usages within buildings and most buildings. While it is possible to connect computers directly to each other, very early the need for intermediate devices was recognized. Local grid controllers serve this function for power. Internet technology has seen several “killer apps” such as email and web browsing that drove technology adoption. We can easily foresee local reliability for electronics, lighting, and refrigeration, and the desire for local generation and storage, as comparable drivers for initial adoption of local DC grids. Initial work on Internet technology was primarily on getting the system to work at all. Efficiency and performance were of secondary importance. The Internet was intended to be a general platform for any type of application or usage context. Attention was also paid to protocol complexity, since this is burdensome in many ways and can introduce vulnerabilities.

VII. FUTURE DIRECTIONS AND SUMMARY

Thomas Edison announced his new power distribution system before he had working hardware to sell [10]. This paper forecasts a future of networked local power distribution even before some critical technology for it to exist has yet to be demonstrated working. Edison created small-scale hardware models of the electricity system he would ultimately deploy. Analog computers were used to model power distribution before digital computers were even invented [10]. Modeling of LPD and nanogrids is needed to better understand the dynamics of local power generation, storage, and dynamic loads, and to assess efficiency, stability, and reliability of LPD and nanogrids.

We need a goal to create LPD technology, first for DC, then adapted as possible and worthwhile to AC circuits and systems. For DC to be successful, and get past the inertia of

our overwhelmingly AC-dominated system, DC needs to enable features that AC systems cannot or do not easily provide. Valuable features are likely to be plug-and-play operation, convenience, cost, and local reliability. LPD can enable these features.

The overall architecture of LPD should not be determined by, or constrained by, limitations of legacy electricity technology; it should be “clean-slate” design. Legacy devices can be accommodated with dedicated controllers or proxies. If complications arise for a specific physical layer or application, that complexity should be confined to that situation so as to not undermine LPD technology generally.

DC power technologies already exist with low power physical layers produced at mass scale. Additional physical layers can be created, with higher capacities, also to be produced at scale to result in low cost products. DC local grids exist in limited form, and will expand over time inside of buildings, taking an increasing share of total consumption. They can grow incrementally as devices become available and features they provide are sought. A recent study estimated the global annual nanogrid market as nearly \$40 billion—ten times the microgrid market [18]. Vehicles may become a key driver for LPD. They are already DC internally, with electric cars having two interconnected nanogrids: a high-voltage one for motive power and climate control, and a low-voltage one for almost everything else. They could enable local reliability by being able to provide power to a building when the grid is unavailable, even if no local generation is present or working.

We are at a time of turmoil and change in power distribution, with the possibility, and likelihood, of a substantially different system than today a decade from now. The overall architecture for this is still very much in development and dispute. This paper offers up criteria to judge such systems, and a coherent vision for such a future that implements these criteria. Such a system can be much more functional for people, and friendlier to the environment by accelerating the adoption of local renewable power.

In this paper we have outlined a possible future for LPD based on a bottom-up and layered model. We have described how nanogrids are the central technology for this new power distribution model. Our model makes sense for the emerging landscape of locally generated DC power, readily available DC storage, and the increase in the number of DC loads in a typical building. LDP is a clean slate design to future power distribution systems unencumbered by assumptions and constraints of the existing century-old AC utility grid.

LPD has obvious advantages for developing countries where utility grids are often non-existent, or unreliable at best. LPD can enable utility grids in industrialized countries to be smaller, less reliable, and much less expensive than today. Utilities will still be a natural monopoly for distribution across public rights of way; LPD does not change that. Utilities might find it desirable to sell different quality and reliability of power to better match customer desires. LPD technology is indifferent to whether utilities never operate on the building side of the meter, or sometimes do. LPD is also part of the global annual

nanogrid market estimated as nearly \$40 billion — ten times the microgrid market [18].

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