Title
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Journal
2024 IEEE 6th International Conference on Direct Current Microgrids Icdcm 2024, 00

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Publication Date
2024-08-08

DOI
10.1109/icdcm60322.2024.10664711

A Power-Centric Digitally-Managed 48V Distribution Technology

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2024 IEEE Sixth International Conference on DC Microgrids (ICDCM) | 979-8-3503-6363-0/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICDCM60322.2024.10664711

***Summary*—Technologies such as USB and Ethernet can be used to power devices in buildings, but have burdens of cost and energy efficiency that make them unsuitable as a primary means of distributing power to most loads in buildings. This paper describes a proposed standard for 48V DC power distribution in buildings suitable for powering most loads in residential and commercial buildings. It includes both general data communication as well as communication for managing the distribution of power. The maximum power is targeted at 1000 W with options for low- and high-power circuits to minimize costs.[1]**

Keywords—direct current; digital power management; local power distribution.

I. Introduction

Power distribution in buildings has changed little in over a century, with exceptions such as replacing fuses with circuit breakers and powering a modest number of small devices with USB and Ethernet. These standards are used for convenience, cost savings, and when reliable high speed data is needed. While they work very well for their applications, these two technologies are unsuitable for broad use in buildings as there are limits on wire length and power levels as well as energy loss from small wire gauge and the electronics needed to ensure high speed data transmission. A few loads have power level requirements that call for higher voltage, e.g. 220V AC or 350V DC [1], but most lie in a range below 1 kW (and most far below). The proposed standard below is intended to fill that gap. Other technologies in use or proposed in this space have significant drawbacks in terms of cost and efficiency [2], proprietary technology [3], or both. We use the name DM48V in this paper for convenience but this is only a placeholder until such time as a standards or other organization takes it up and assigns a technical or marketing name; DM is for digitally managed.

DM48V is optimized for power distribution while also transmitting data. The design is intended to minimize cost and efficiency overheads while maintaining high performance and flexibility. It adopts principles from USB and Ethernet such as permission-based capacity, but adds capabilities from the Local Power Distribution (LPD) technology [4, 5] that can facilitate grid integration and future networks of 'nanogrids'. We have created a hardware demonstration that implements core capabilities. The solution described here can be the start of a process for moving to a future in which most power distribution in buildings is digitally managed.

[1] This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

II. Methods/Results

The foundation of DM48V is that used in products currently available from Domatic, Inc., and facilitates nominal 48V DC distribution to loads on circuits up to 100W. This limit allows circuits to be treated as communication wiring under the National Electrical Code (NEC) [6]. There is no limit on the number of loads on a circuit so long as the power limit is respected. The power is accompanied by IP communication to control loads and a simple but extendable set of application-layer mechanisms. The communications are carried on the powerline by the IEEE 1901 broadband networking standard [7] to leverage commodity components that implement that standard.

This technology has a variety of advantages compared to typical practice:

- Low-cost installation as it does not require permitting or installation requirements of conventional wiring.
- Facilitates the use of thinner wires than AC, which require less copper, use smaller holes, are lower cost, and are easier to install.
- Circuits and connections are easier to modify.
- With digital control, control is defined by software, not wire runs.
- Centralizing the AC/DC power supply increases efficiency, and reduces costs and failure points.
- Integral data communication supports devices like touch screens and speakers.
- The wide range of load supply voltages and use of variable wire gauges and lengths allows for system flexibility and prioritizing efficiency.
- Devices with occasional high power requirements can have integral storage to stay under 100W.

We have layered on top of this several new features:

- LPD messaging (see Table 1),
- The ability of ports to carry > 100W,

- An integrated battery directly coupled to the DC power hub, and
- Grid Controller[2] (GC) capability for the Hub as defined by LPD.

The basic messages for LPD are listed in Table 1. These may be supplemented by features for voltage management.

All four messages are used for 'downstream' links to loads. For links between GCs, the Request message is not used but the Allocate message is used in both directions. The prototype hardware that we created lacks upstream ports for connecting two or more GCs, but these can also be DM48V links.

Figure 1 illustrates the concept of Digitally Managed Power; whether the three components are on the same wires (as with Ethernet) or different wires (as with USB) is an implementation detail; what is important is that they are in the same cable.

Advantages created by the extended technology include:

- Price response improves system operation whether grid-connected or (especially when) not.
- Batteries can provide value either in loads or in infrastructure devices with price response and local reliability.
    - Distributed batteries have advantages with efficiency and ease of deployment.
- Devices can be supplied that have much higher power requirements.
- More devices can be covered by a single hub, amortizing its costs and power requirements.
- The hubs are nanogrids and so building blocks of a mesh network of nanogrids within a building[3].

TABLE 1. BASIC LOCAL POWER DISTRIBUTION MESSAGES FOR LOADS

Message	***Description***
Register	Device connection, disconnection, and link configuration
Request	Load requests authority to consume a power level from a GC
Allocate	Grid Controller grants a specified level of power to load/GC
Price	Grid Controller broadcasts the local price to connected devices (loads or GCs)

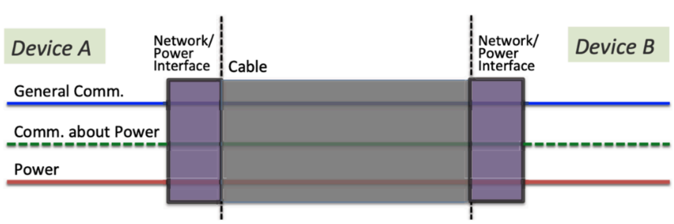

FIGURE 1. DIGITALLY MANAGED POWER

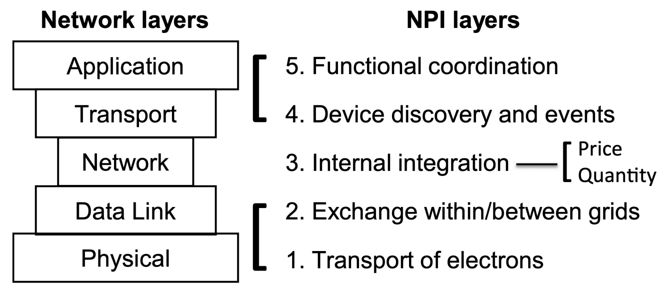

FIGURE 2. NETWORK POWER INTEGRATION

Underlying Digitally Managed Power is the concept of Network Power Integration (NPI; see Figure 2) [4]. NPI completely separates the technology domain of power distribution from the domain of functional control, just as the OSI model separates physical layer technologies from application layer protocols.

DM48V includes traditional Domatic *low-power* circuits (<100W) in addition to *high-power* circuits that would allow power levels up to 1 kW[4], also with multiple loads per circuit. The latter would require thicker wires than usually used for Domatic circuits and be subject to the same protection requirements for general wiring described in the NEC.

A grid controller could have low-power and/or high-power ports, or a 'bridge' device (see Section VI) could allow multiple low-power circuits to be powered by a high-power circuit. This allows trunk lines of higher capacity, with less expensive wiring closer to small loads.

III. ALTERNATIVE TECHNOLOGIES

There are other 48V technologies available today, so an obvious question is whether any of them are sufficiently suitable substitutes for this one. We presently lack specific details such as cost and energy efficiency for most, and these two factors are also highly dependent on the particular application context (e.g. circuit topology, wire lengths, wire gauges (when discretionary), installation costs, etc.). With that, this is necessarily only a high level overview.

Only the first two technologies (USB and Ethernet) have substantial industry uptake and only Ethernet is hosted by a formal standards development organization. Such institutional support (SDOs and/or trade associations) is important for wide market success.

USB. Universal Serial Bus has always been digitally managed and has the advantage of existing high market penetration. It is highly functional for connections that are only short distance, often temporary, and not permanent. It also supports high-speed data transmission for applications where that is important. It essentially covers an application space different from that of DM48V and so is complementary, not competitive. DM48V could readily support having a USB output as a load.

[2] A grid controller plays a role analogous to that of an Ethernet switch in an Internet Protocol network.

[3] This does require adding upstream ports to connect two or more grid controllers; our prototype lacks these.

[4] High power ports; we have tentatively assigned 1 kW as the maximum power as that is approximately what 48V provides with 12 gauge wire. The actual limit would be defined by current and could end up being lower or higher than this level.

Ethernet. Ethernet is suitable for either temporary or permanent installations. Its primary purpose is high-speed data transfer, and it can cover very long distances. The traditional 4-pair Ethernet can carry up to 90W to a single device with the most recent update to the standard. The more recent Single Pair Ethernet (SPoE when power is applied to the cable) has been more adapted to carrying power. There are multiple versions available or in development including one that is multidrop and so more suitable to powering applications. This also allows for more choice in wire gauge to be able to optimize a given installation more for material cost and energy efficiency.

Ethernet is the technology most closely related to DM48V. Ethernet does carry a burden in supporting high-speed communications in hardware costs and energy, though this can be mitigated by optimizing design for components for which power is more primary. As DM48V does not support the reliable high speeds of Ethernet, to a great degree the two are also complementary.

VoltServer. VoltServer provides safe transmission of high levels of power over relatively long distances by using high voltages (e.g. 400V) and pulsing the DC power to enable detecting possible faults. These features also come with energy and hardware cost burdens that make it unsuitable for the application space we are targeting. VoltServer could be useful in combination with DM48V for installations that require long distance transport of power to the location of a 48V hub. VoltServer's data communication capabilities are unclear, but a VoltServer cable could be readily accompanied by an Ethernet cable for carrying the data.

LumenCache. The LumenCache ReNetA system facilitates using multiple physical layers for distributing power and data. It is oriented to lighting though also includes related loads such as fans and USB outlets. It is designed to be highly modular to enable evolving to new distribution technologies as they become available.

ATX LED. As its name suggests, ATX LED is focused entirely on lighting. It is highly optimized for cost and energy use but is not a general power distribution technology.

Sinclair Digital. Sinclair Digital grew out of PoE technology but

None of these technologies has the same goal as DM48V. Some are data-centric. Some are lighting-only. Some solve other problems (e.g. high-power long-distance transfer). DM48V is intended to be a general mechanism for power distribution for any small device – and some that require medium power levels. Lighting is certainly a significant part of this, but DM48V is generic. None of the other alternatives have the same combination of performance, capability, energy efficiency, and cost efficiency that we are aiming for. Some of the alternatives have capabilities that our technology does not attempt to provide and so are necessary parts of a complete DC future.

IV. Prototype Design

Our central goals for DM48V include that it be energy efficient, low cost, have high functionality, and include Local Power Distribution capability. We found a technology already on the market that included the first three, from Domatic Inc. [8], and have built our proposal on top of it. The Domatic system uses IEEE 1901 to provide Internet Protocol communication, and limits power on each port of the system hub to 100W to ensure that the circuits are treated as communication wiring. The Domatic hub provides application-layer device management, such as integrating switches and light sources. In its target market domain, systems are pre-engineered in topology so that each port has less than 100W of connected load, ensuring that the capacity cannot be exceeded. With this, Domatic does not need to actively manage capacity, and does not have any power distribution functionality.

To this base, we layered in the LPD technology – which has no application layer functionality. With this, our prototype includes both mechanisms, but each of them is unaware of the existence of the other, so there is no communication between the hub and grid controller software (loads do communicate with both). In the Domatic system the central hub coordinates among the connected devices, and intelligence within each attached device. A separate PC hosts the central LPD functionality of a grid controller. Each Domatic load has a processor to host necessary load communication. To avoid having to modify the load software (embedded code so not easy to do), we host a process on the LPD PC for each load to carry out its LPD functionality.

a. *Software Design*

Figure 3 shows the two central communication elements – the Hub and LPD PC – and how messages are passed between them and the load devices. Both the Hub and PC host endpoints for messages to pass through. In a normal implementation, messages pass directly from the hub to loads. In our system, the Hub instead passes messages via a 'load agent' for each load. That agent implements LPD functionality, including exchanging messages with the GC software. The load agents also communicate with the loads themselves. The Hub communication semantics are unaffected. In the course of implementing the prototype, nothing arose to compromise the the original goal that the two central systems should be unaware of each other.

The GC software also communicates with the battery, as we implemented the battery controller as a separate device that uses USB communication to the controlling device. In LPD, the battery is logically inside the GC. The prototype also includes a programmable load on a new circuit that uses thicker wires and is treated as ordinary electrical wiring. This was more convenient than using many existing Domatic loads and postponed the need to create the circuit to add IEEE 1901 to the higher power domain. With this, while we use IP communication to a Raspberry Pi that controls the programmable load, this will not be part of a more advanced demonstration and so is not shown in the figure.

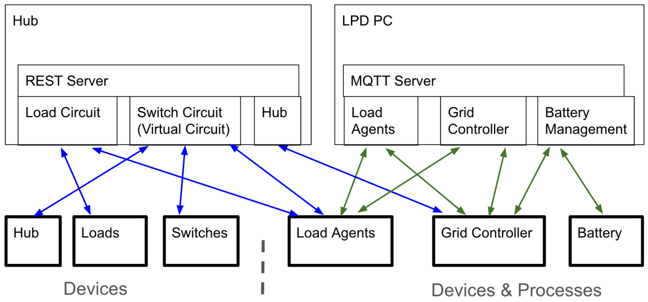

FIGURE 3. PROTOTYPE SOFTWARE ARCHITECTURE

We did not host the new communication endpoints on the Domatic hub which maintains the separation of functionality between the two domains. The original LPD software was a single-threaded system in which messages were passed through function calls. A 'supervisor' entity in the software choreographed the exchange of messages and managed the advancement of time, to ensure that all actions occurred in the correct chronological sequence. This worked very well for simulation, but for our prototype we wanted to explicitly pass messages among software that was, or would later be, on different devices. With this, we reconfigured the LPD software to be multi-threaded to be able to facilitate communication with the other devices.

Our LPD load agent software for lights had parameters to cause them to begin dimming below the requested brightness level when the price exceeds a threshold. The brightness level then drops linearly until a second price level is reached at which point it then drops to a final level and remains there. We also allowed any light to become an 'emergency light' by having it turn fully on at the highest possible price. This price is used to convey that the AC grid connection was lost. Loss of AC power is best understood as a functional control signal, because it is not directly about the availability of power within the nanogrid.

All of our Domatic loads were ordinary light fixtures which could operate as lights, or be commanded to consume a particular power level by software that simulates a different device type. We implemented software to simulate a simple refrigerator or freezer. For these, we tested two different algorithms. In the first, the local price directly drives the setpoint that is to be maintained. The second algorithm recreated that used in [9] in which the setpoint is adjusted slowly over the course of the day and night (based on a price that is constant at night and lower to varying degrees during the day. This second mechanism causes power draw to resemble a PV peak when the price is constructed based on an inverted PV shape.

To make testing practical, we dramatically sped up operation. While a normal compressor on cycle is about 20 minutes, we reduced this to a few seconds. While price changes might commonly be once an hour from the grid (and never faster than five minutes), we changed prices at intervals measured in seconds. This was not a meaningful difference for the LPD software. The battery would require several hours to charge or discharge at power levels that the Atverter supported so we only did this only in a few battery-only tests. For our other tests which included the battery, its state of charge did not change meaningfully over the several minutes that each test took.

b. *Hardware Design*

The prototype did not require any modification of the Domatic system. We added hardware between the AC/DC power supply and the Hub: the battery and a programmable load. The section of wire between the power supply and hub forms the high power port for the prototype, though the high power port is missing IEEE 1901. The battery is controlled by an Atverter [10] that communicates with the LPD PC over USB. The LPD PC is not electrically connected to the prototype as it only provides communication and computation. Figure 4 shows hardware components and electrical connections.

The Atverter controls the voltage seen by the battery to accomplish charge and discharge, and also estimates the battery state of charge. For convenience, a pair of 12V batteries were used for 24V with the Atverter converting the DC voltage as part of its operation.

The battery and LPD software for the grid controller are logically part of the Grid Controller. .

Figure 5 shows a photo of the system components. From the top on the left are the power supply, Domatic hub, the green Atverter, and two 12V batteries. On the right are the four light fixtures and a switch for manual operation. Not shows are the programmable load and measuring devices.

V. PROTOTYPE EVALUATION

Evaluation of the prototype performance occurred in two steps: component testing, then full operation.

Our primary electrical monitoring of the prototype was an AC power meter for the power going into the power supply. It recorded data at approximately two second intervals. With this, we made sure that the LPD intervals were at least 4 seconds long so that there would always be at least one full interval corresponding to each power level in the system.

Functional verification consisted of exercising each part of the hardware separately or in combination: loads (lights), programmable load, and battery. Loads can be set to a wide range of brightness levels, the battery can be set to charge or discharge at a specified power level (or do nothing), and the programmable load can be set to a wide range of power levels. Each component was tested separately to confirm correct operation as observed by the AC power meter. All battery discharge tests were performed so as to maintain at least a few W flowing through the AC supply at all times.

The power supply used was rated for 150W and could only output about 170W before tripping off. With this, we limited testing to levels below this at the AC supply. We were able to draw more total load power when the battery was discharging to cover part of the load. The hub itself consumes about 10 W DC.

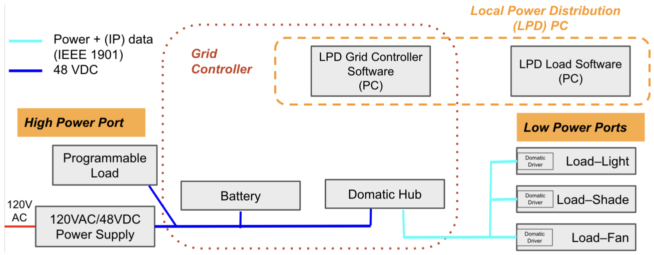

FIGURE 4. HARDWARE ARCHITECTURE

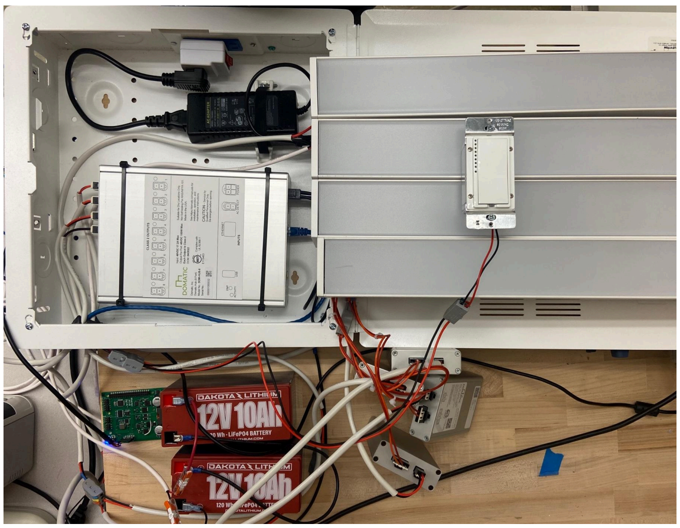

FIGURE 5. PROTOTYPE HARDWARE

During these tests we monitored the DC bus voltage to confirm that it did not deviate significantly from the nominal voltage. The component tests all showed correct system operation. The lights not surprisingly had an initial fixed consumption to turn on at all, then had power levels that increased linearly beyond that. This value was pulled into the load agent software so that the correct capacity would be requested for a given brightness level. The Atverter takes a number of seconds to transition from one power level to another rather than doing so in a fraction of a second. This is not an issue when connected to a larger grid, but is for other purposes such as islanded operation. A test was done to verify off-grid operation by cutting the AC supply without warning to confirm that the Atverter could maintain the bus voltage during the transition (at least for some levels of power consumption).

The second phase of testing brought the LPD software into the communication paths and determined system operation. Simple test scenarios were created to turn lights on and off and operate a refrigerator or freezer via the programmable load, all while varying the price.

The system tests that included the LPD system were primarily just confirming that the power levels observed in the hardware corresponded to those produced by the LPD software. The LPD software was originally only used for simulations and so was known to work (though we did add the freezer capability in the course of work on the prototype). Prior simulations included multiple grid controllers as well as PV and a utility grid connection, with each GC havings its own local price. Thus, the real purpose of these tests was to confirm that all of the communication between the hardware an the LPD software operated as intended and that observed power levels were as expected.

Figure 6 shows the computed power level from the LPD system and the measured power of the hardware prototype with the four lights and a freezer. The measurement includes the losses of the power supply.

Next we show a test with four lights and a refrigerator. Each light has a different price/brightness response curve, and one of the lights also functions as an emergency light. The refrigerator in this case implements the simple algorithm with the setpoint directly tied to the current price. All devices work as expected, and the measured power tracked the computed power similarly to the first example.

In this case we used a price of $1.00/kWh to also reflect a grid outage to cause the emergency light to come on. Note that this does not affect refrigerator consumption as it never uses a setpoint above its programmed acceptable range. The pattern of prices is shown in Figure 7.

Figure 8 shows the refrigerator temperatures (setpoint and actual internal) and power consumption (instantaneous and averaged over each full on/off cycle).

Figure 9 shows all of the light power consumption patterns. Each light has a different function and parameters. Light1 is an emergency light and so stays on for the emergency time late in the simulation, but is otherwise the lowest priority in that it dims first and most with higher prices.

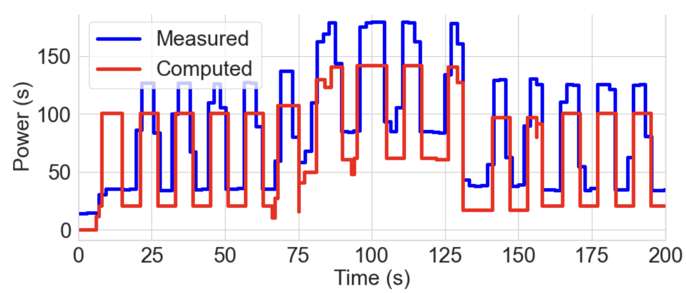

FIGURE 6. MEASURED AND COMPUTED POWER

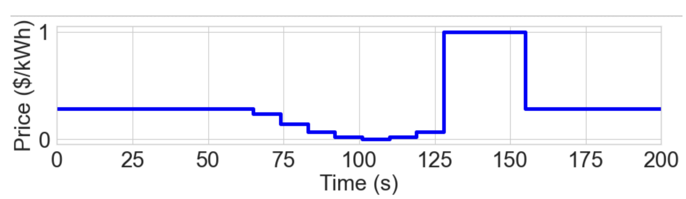

FIGURE 7. PRICE USED TO DRIVE THE SCENARIO

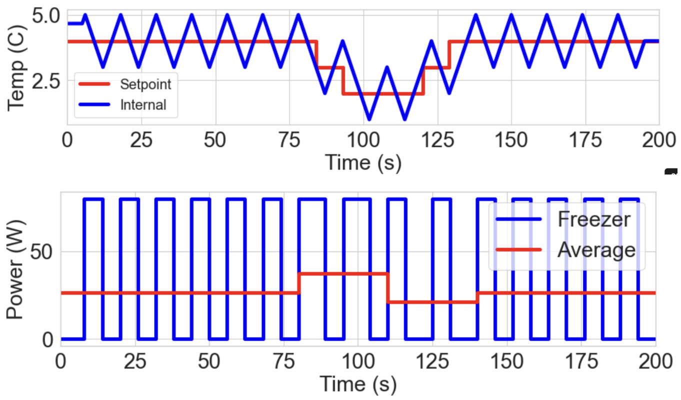

Figure 8. Refrigerator Temperatures and Power

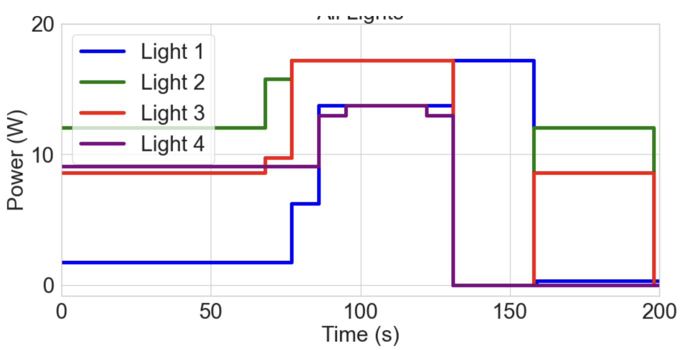

Figure 9. Light Power Levels

While the complexity of our demonstration system is quite modest, with only five loads, our prototype correctly implemented all planned capabilities. With this hardware demonstration, we have created the world's first fully functional isolated nanogrid controller[5], demonstrating functionality analogous to what the Interface Message Processor did for computer networking back in 1969 [11].

That said, our prototype does not include the capability to exchange power with other connected GCs, it can't operate in a network of nanogrids. This should be part of some phase of future work. That said, standardizing the technology even only as tested so far would be useful in moving forward DC distribution in buildings.

VI. Next Steps

There are a variety of additions to the functionality of our system and changes in prototype implementation that we have planned.

a. Streamlined hardware

Development of the initial prototype uses a separate computer for the LPD computing to simplify debugging. For the next version of the prototype we plan to have that software run directly on the hub, in a software container to ensure that it cannot disrupt the hub's overall operation. This removes the separate PC and is necessary for any practical product. The only open question about this is what mechanism to use to communicate with the battery.

A second modification is to create a circuit to apply IEEE 1901 communication to the high power port. For the existing Domatic hub, this could use one of the existing Ethernet ports as the data path. We don't expect any difficulty in creating this hardware. While the high power port could simply power existing Domatic loads, it would be useful to create some working ones that routinely draw more than 100W, e.g. a working refrigerator or freezer.

b. Load agent location

The software that implements LPD functionality for loads could continue to reside in the hub, or could be moved to run on the loads themselves. For devices that make decisions internally (as a thermal appliance does), this is necessary. A single future hub could host a mixture of these without difficulty; the only issue is that the hub would have to know what type of device each was to facilitate the proper messaging (that is, sending communication directly to the load, or to a separate load agent). In fact, a hub could also support non-LPD loads, though the GC would have to assume maximum capacity requirements for each of these loads at all times since they wouldn't ever request needed capacity themselves.

c. GC-GC power links

To fully realize the vision of networked electricity, it is necessary to provide for power links between grid controllers. The link technology used on the load side of the Hub would be adapted to serve this purpose. There would need to be additional power electronics at each end of the link to manage the voltage and current on the link and possibly coordination about voltages.

Initially at least – and possibly always – such links would be limited to two devices. Having more devices on such a link greatly increases the complexity of the communication and electrical engineering involved. It is possible this might never be worth it.

d. Dynamic voltage management

We also plan to explore how the technology could be extended to manage voltage through monitoring voltage at each load and ensure that power is not allocated in a way that will lead to any load receiving less than its minimum voltage. This can enable being more flexible about wire gauges and length while respecting technology limits. Also, while today the Domatic minimum voltage is 40V, this type of capability would allow devices to communicate their minimum voltage to the hub which might be higher or lower than 40V.

Conventionally, power distribution systems either provision infrastructure so that all devices can run at maximum load at the same time, or use circuit breakers to cut power when limits are exceeded. Wire gauges and maximum length are also specified to not exceed voltage ranges. Both lead to most deployments over-provisioning infrastructure capacity. With digital power management, power on each port can be limited to not overload capacity, and with strict

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requirements for wire length and gauge, it can be assured that each device gets the power and voltage it needs. It also would be advantageous to be able to be more flexible in wire length and gauge, but this raises two risks that need to be addressed: minimum load voltage and wire segment capacity.

DM48V has a 60V maximum voltage at the hub, and a 40V minimum voltage at the load. This could lead to a loss of as much as one third of supplied power, which is naturally not ideal for ordinary use, but could be useful in niche applications (e.g. very long cable runs or devices with and modest energy use (from intermittent operation or low power levels). Many installations might take a lower voltage in (e.g. closer to 48V). The Ethernet standard includes an AutoClass function that allows a supplying device to command a load to consume its maximum power level. Coupled with the ability of a load to report the voltage it sees, the voltage drop between the hub and load can be calculated. At system startup, each device can be subjected to the AutoClass function individually, and in groups.

With this information some degree of mapping of the wiring topology can be done. The technology allows for an arbitrary tree structure of wires. Devices that share wiring will have an effect on the voltage drop of each other when both are powered, and the more shared wire the larger the effect. The AutoClass is the maximum power but devices will commonly request capacity for a lower power level. With this, we expect that capacity can be allocated in a way that assures that no device will have its voltage drop below its minimum. That said, we need to test this in simulation and then in hardware to be certain that this will work well.

This is unexplored territory and both simulation and empirical testing will be needed to see if any major or minor issues arise that limit how this can be utilized. For loads this approach is clear. A load such as a USB port powered by DM48V would need to somehow consume its maximum load on startup. As USB already includes permission-based capacity, USB device requests for capacity could be simply relayed up the chain to the GC (adding the power overhead of the USB port itself of course). Loads with some non-digitally managed output would need to request the maximum possible power they could provide at startup.

Another issue this raises is ensuring that no segment of wire exceeds its current capacity. We plan to explore if a combination of electrical measurements and wire installation heuristics can satisfy this requirement. Clearly if details of the wire topology were provided to the hub then it could ensure safe operation. Rules could be established about sizing connected wires in such cases. Some installations will be engineered and so have this information available. Other deployments will be more informal or dynamic and so won't have such data and/or don't want to rely on its accuracy.

A final possibility is dynamic input voltage to the hub. In current Domatic deployments, hubs receive a constant voltage level from a regulated power supply. In the future it may be convenient to allow for the input voltage to vary. This would need to be specified within some range and loads would need to report if their power level varies with voltage.

e. Bridge Devices

Another next step is to create a simple 'bridge' device that connects a high-power and one or more low-power circuits. The bridge has the following functions:

- Provide power limiting to downstream low-power circuits; this is the same functionality that the hub implements, to cut power to the circuit if the capacity is exceeded.
- Report limit exceedances to the hub, and restart the circuit after a suitable delay. Loads are programmed to start in an off state after a power cycle to avoid repeated exceedance cycles. The hub can turn off the auto-restart if a load misbehaves and causes multiple successive exceedances.
- Report the power or current for each low-power port so that at startup the hub could determine which low-power port each load was on to ensure that capacity is not over-allocated.
- Possibly report voltage if this turns out to be important for dynamic voltage management.

While bridge devices would be quite useful, they wouldn't change GC operation very much. The tracking of capacity allocation would need to be for both the remote low-power circuits in addition to the high power circuit they draw from, as a bridge might well be oversubscribed for capacity (not be able to power all downstream ports at their maximum power level).

Figure 10 shows different possibilities for the structure of high and low power links and hubs. The right example has bridge devices to transition from high to low power circuits.

f. Standardization

This technology could be embodied in a technology standard under the auspices of a suitable standards organization. The technology standard would cover aspects such as voltage, cabling, the physical layer of communications, standardized device classes akin to USB, and ideally a standard connector. The LPD concepts for managing the distribution of power in a network would be codified in a separate standard from the link-level standard for point-to-point transmission of digitally managed DC power. The reason to separate the LPD messaging is to enable it to be reused by other such standards, e.g. one for higher voltage power. We do plan to create a more compelling prototype as described above before presenting it to a committee; this would probably include all of the streamlined hardware and a bridge device; we would probably not wait to fully explore voltage management before starting standardization discussions.

We are also interested in defining a standard connector for plug-in devices. This is probably best left to a standardization process since it doesn't affect the rest of the technology.

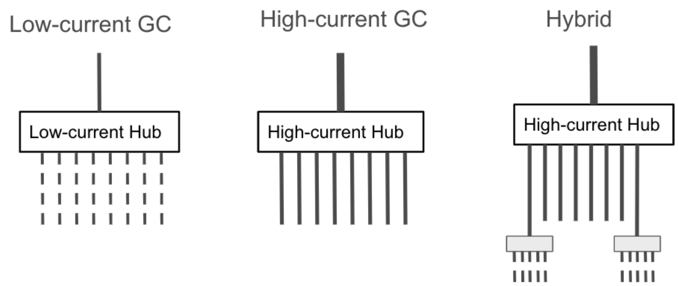

FIGURE 10. Deployment Options with diverse Circuits and Hubs (dashed lines low-current; solid lines high-current)

g. *Higher voltages*

The prototype can also serve as an initial example for other physical layers of power distribution. A notable need is for one that operates at higher voltages (e.g. 350V) and consequently higher power levels. Applying IEEE 1901 to a 350V line might be problematic, and even apart from this a better approach might be to have cables with four wires in them – two for the 350V power, and two for DM48V. In this model, a load would initially draw zero power from the high voltage wires and use the DM48V link to obtain power for controls and to request power on the 350V line. Only after receiving an allocation of sufficient power would the load draw any power from the 350V lines.

GC-GC links at higher voltages would also be quite useful, particularly in integrating PV and vehicle charging into the digitally managed domain. What power levels might be appropriate here we leave to others, though for reference, the 20A target for high-power 48V links would result in 7 kW of capacity at 350V.

VII. Conclusions

Most loads in buildings today are small in maximum power, internally DC, and would benefit from communication capability. These all point to the need for a 48V DC distribution technology that is power-centric and that is designed for generic loads (i.e. not just lighting). This technology can serve several purposes:

- Cost-effectively powering small DC loads, particularly lighting and electronic devices.
- Serving as a foundation for ‘networked electricity’ with Local Power Distribution.
- Reducing barriers to integrating local renewable sources and storage by decoupling these from the AC grid.
- Reducing costs for local reliability.

The technology extends what is commercially available today by adding the option of higher power circuits, and the digital management capabilities of Local Power Distribution. Once standardized, a rich ecosystem of loads, grid controllers, and related devices can develop, all interoperable for power distribution. These will be suitable for deployment in any building type, including related markets such as on the exterior of buildings and in and around vehicles.

The success of digitally managed power at this voltage can then set the stage for developing a similar standard at a higher voltage level, e.g. 350V, with higher power levels. Ultimately this can be a building block for relatively lower cost microgrids to enable local reliability at any site.

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