Modular power manager and gateway: an approach to home-to-grid energy management and demand response

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Abstract:

New modular premises devices that combine the functions of a smart power manager integrating inverter, charger, power conditioner, meter, and demand response controller can provide comprehensive management of energy within a premises. Such devices facilitate the incorporation of renewable generation, as well as management of storage, and use of electricity, whether connected to a grid or not and whether communicating with a utility or not. These benefits are enhanced by a modular communication gateway based on international standards that can provide additional functionality by providing interconnection and interoperability between in-home networks and equipment and external networks and service providers.

This paper describes the general problems of residential energy management and how power management equipment, in combination with smart appliances and home networks can address these problems. It describes one particular device and architecture as a comprehensive case study. It examines the problem of demand response on time scales of hours, seconds, milliseconds, and minutes and how this equipment can work both independently and in connection with a grid provider. The paper presents these elements within the context of the GWAC stack framework focusing on basic connectivity and interoperability.

1. Introduction

At the bottom of the smart grid "food-chain" is often found the home or small building. It is there that energy is ultimately used, and perhaps in the future, also generated or stored. Advanced utility industry demand-side management approaches are being taken to electric power in homes and buildings. In particular, the idea of distributed energy resources (DER) and active demand response (DR) systems are being devised, including various transactive control strategies (e.g., reliability and real-time price signaling). Application of these approaches requires communication to the home and among appliances within the home using a wide variety of existing networks, protocols, and products. In addition, much can be done on-premises to manage power in a way that complements the grid and active smart grid DR strategies.

1.1 Scope

This paper describes the general problems of premises energy management and how power management equipment, in combination with smart appliances and home area networks (HANs) can address these problems. The paper describes one particular device and architecture as a comprehensive case study. It examines the problem of DR on time scales of hours, minutes, seconds, and milliseconds, and how this equipment can work both independently and in connection with a grid provider.

The critical elements of this architecture include an intelligent Power Management Agent (PMA) and a standardized gateway[1] enabling communication between external networks (including grid utilities) as well as with and among home networks and various appliances (including power management equipment). Such a gateway situated between the home and the grid has been identified as the Home Energy Services Interface (ESI).[2] The PMA would run on the ESI gateway and communicate with local loads and generation devices as well as other PMAs that potentially reside in the same home or in the community.

These elements are presented within the context of the GridWise Architecture Council's GWAC stack framework[3] dealing with lower *Technical* layers of basic connectivity and syntactic and network interoperability, but also with the middle *Informational* layers, in the realm of *Home-to-Grid* applications.

1.2 A bottom-up perspective

From the perspective of the utility or grid operator, there is a natural inclination to look toward the home or building from the top down. From such a perspective, the *smart grid* is seen as a part of a supply/demand management problem beginning at the generating station, working through the distribution grid, down to the home or building, and ultimately all the way to its individual appliances. Centralized grid management is already a complex control system, and extending it into homes and individual appliances creates even more complexity. Cox and Considine have observed that "[smart grid]…diversity of purpose can never be supported by unitary control strategies… [i]f the end nodes are forced to accept direct control from the outside…"[4] They conclude that that "Greater response from end nodes must come from engagement rather than control."

Therefore, it is suggested here that there is another way to look at the overall problem that may ultimately be simpler—a bottom-up view that sees the home or building as an "island" that generates, uses, and stores power—like an RV or a boat. From this perspective, the power management problem becomes one of managing local resources and the grid becomes merely another storage device— a battery to be charged and discharged. With the widespread incorporation of distributed energy resources (e.g., solar and wind), every home becomes a potential generator, user, or storer of energy. This energy can be first managed locally (i.e., within the premises) and then within the community and the grid. Such a perspective offers to greatly reduce the demands on the grid and simplify the overall control problem. With this simplification, when combined with advanced transactive control schemes (e.g., real-time dynamic pricing mechanisms)[5] the problem can be simplified even further.

2. Basic architecture and elements

A useful emerging concept is the *microgrid* [6] [7]—an autonomous or semi-autonomous grid that can operate with some degree of independence from the regional grid. A microgrid can be as small as a single home, or can include an entire neighborhood, as large as a campus, factory, or small city. For purposes of this discussion, the smallest microgrid that can support all of the basic elements may be referred to as a *nanogrid*, and it can function as an effective element of a larger microgrid or a regional grid, offering to assist in the balancing of both the supply and demand for electricity. In order to provide such functionality, the nanogrid may include some or all of the following elements:

- Power using elements—appliances or other loads (resistive or reactive)
- Power generating elements—solar PV, wind turbines, generators, etc.
- Power storage elements—batteries, EVs, etc.
- Power conversion or conditioning elements—inverters, chargers, power factor compensation devices, etc.
- Power managing elements—sensors, switching devices, DR controllers, etc.

- Communication network elements—WANs, HANs, gateways, routers, etc.

Figure 1 depicts a generalized home nanogrid model representing the possible nanogrid elements. The oval shape represents the gateway or sensor and the circles represent power-using appliances that can communicate via a HAN. The rectangular shapes represent energy-using appliances that are not able to communicate and must be directly controlled by their power circuits. The octagonal shape represents a power management device or "power manager" that includes functions of inverter, charger, power conditioner, and DR circuit controller.[8] The cross shapes represent power storage devices. The triangular shape represents a power-generating device. The solid arrows represent a power path and the dotted arrows represent a communication path. The WAN is any external access network such as cable, DSL, wireless, powerline carrier, etc. The meter is the grid connection and premises service entrance.

The central elements in this nanogrid model are the *gateway* for managing communication and the *power manager* for managing power. The gateway in this case is the *HomeGate* HES gateway specified by ISO/IEC 15045 HES *Gateway* and ISO/IEC 18012 *Guidelines for Interoperability*, described by Schoechle (2009). It defines a modular platform for appropriate network (HAN and WAN) interface modules and application service modules. The power manager in this case is the *Heart Transverter*™ (Heart, 2010) system and is comprised of a modular array of related power management devices including up to 12 power (smart inverter/charger) modules, a circuit switching/data logging (T13X) module, and a control panel module. Other "smart inverter" power management equipment with a similar architecture, comparable functions are also available.[9]

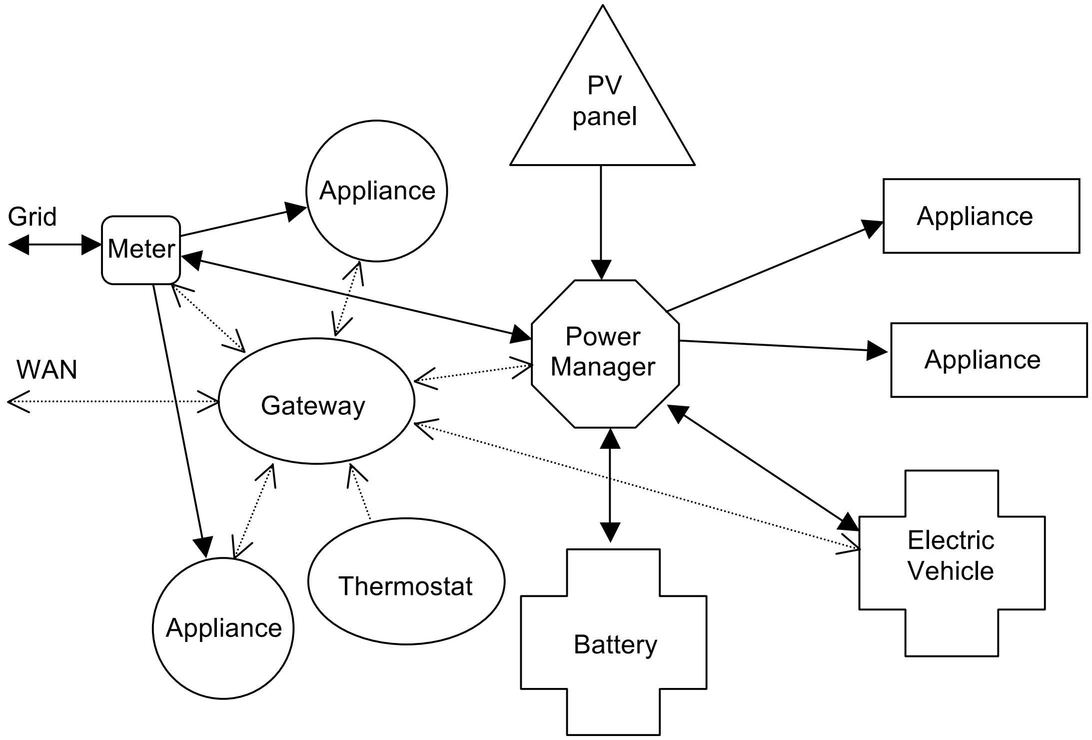

Figure 1 — Home nanogrid model

3. Gateway element

The gateway element provides a distributed, expandable modular platform—based on a kind of "Lego™" block model—that consists of a number of network (HAN or WAN) interface modules appropriate to the specific home/nanogrid case, a number of application service modules also appropriate to the specific case, and a connecting "gateway link" event bus among the modules. This architecture is depicted in Figure 2.

The specific communication protocols and languages employed in the system and their respective control semantics are beyond the scope of this paper and are the domain of other standards or proprietary products. In any case, the ISO/IEC 18012 interoperability standard embodied in the 15045 gateway standard is intended to accommodate any and all such protocols and languages and render them interoperable, without modification.

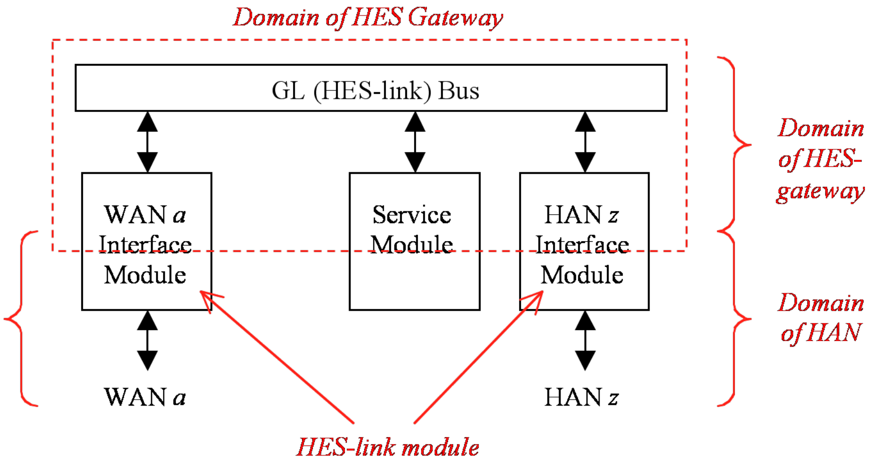

Figure 2 — HES gateway architecture

Interoperability among all modules and networks is provided by an implementation of the ISO/IEC 18012 *Interoperability* standard on each module.

4. Power management element

The nanogrid's power management element, exemplified here is the *Heart Transverter™* system depicted in Figure 3. This system is comprised of 1) up to 12 HT2000 (inverter/charger) power modules, each with a capacity of 2400 Watts, 2) a T13X switching/data logging module capable of switching up to 6 independent 30 Amp 60 Hz AC or DC circuits, and 2) a control panel module with a USB port. All modules are interconnected by a proprietary data bus and the power modules can be interconnected by a 50 VDC shared power bus and a 110 VAC 60 Hz synchronized power bus that can either feed power into or pull power from the grid.

This section further describes how the power management element can contribute to the stability of the grid and to the incorporation of renewable distributed energy sources in to the grid as well as provide for the needs of the home. It also shows the benefits that may be achieved by approaching the smart grid from a bottom-up perspective beginning with the individual home or building as the smallest autonomous or semi-autonomous unit.

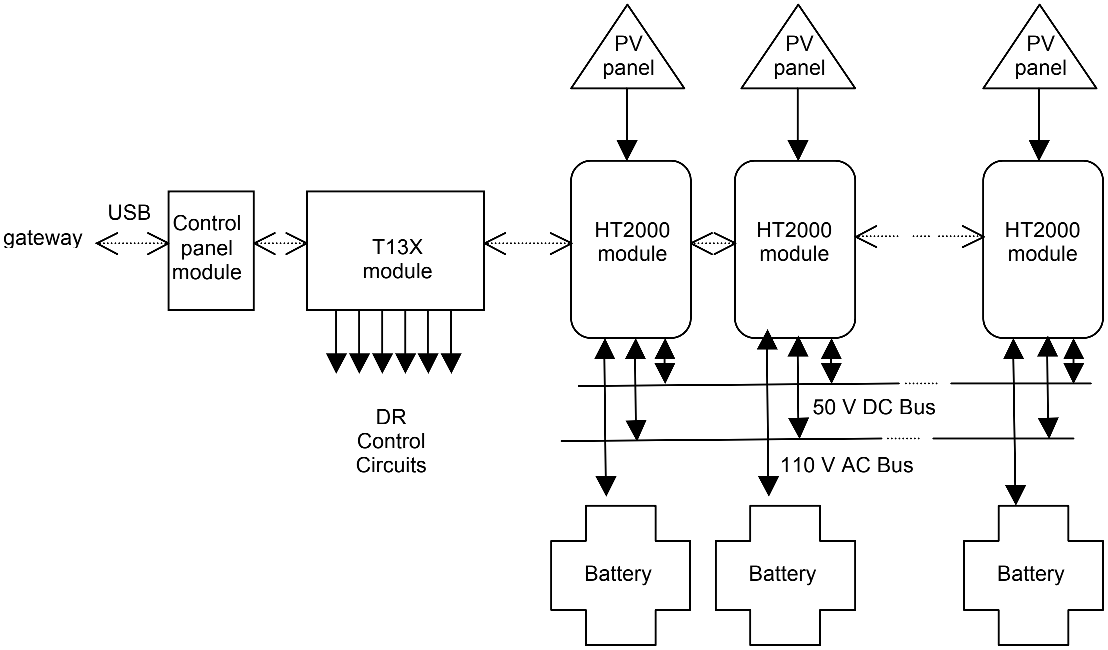

Figure 3 — Transverter™ architecture

4.1 Power management functions of the Transverter

The power management functions can help manage electrical energy through the leverage provided by on-premises power conditioning or power conversion capabilities. Such power conditioning/conversion sub-systems work in conjunction with on-premises management generation, storage, and use. They may include the following functions:

- Solar PV inverter (DC from PV to AC grid)
- Smart battery charging (AC from grid to DC to battery or PV to battery)
- Battery feed to grid
- Automatic surge assist
- Grid frequency monitoring (detection of grid overload and automatic response)
- Power factor compensation
- Grid event monitoring and data logging
- Smart metering
- Customer display and control

4.2 Demand response strategies

The Transverter's power management functions can operate in an autonomous or semi-autonomous mode (with or without grid or utility communication or intervention) implementing DR strategies with or without active grid interaction. The intelligent PMA residing on the gateway platform could manage such functions. These elements can operate to manage power on-premises and enhance grid stabilization on a time scale of hours, minutes, milliseconds and seconds.

4.2.1 Demand response – hours

This form is conventional DR and operates on the basis of signaling from a utility. It operates over a time scale of hours. High-speed grid communication capability is not required. The local PMA could provide switching control of several circuits for smart demand control for appliances such as refrigerators, air conditioners, etc. A more intelligent approach uses a PMA that never actually turns any thing off or on, but just changes the settings of the thermostats, or senses pressures or other parameters that have immediate impacts on energy use, but would otherwise require intelligent appliances. This form of DR can keep the grid from having to engage auxiliary and more expensive (i.e., marginal generating) capacity during times of peak use.

4.2.2 Demand response – minutes

This form consists of locally distributed renewable energy generation also with grid communication, and it operates on a scale of minutes. It not only puts renewable energy generation on "free" local real estate, but the power could be consumed locally so nothing would be lost to transmission. This form of active DR can contribute greatly to grid stability, while the PMA at each node could continue to operate as needed. Similarly, turning off or diverting PV or other local generation could be just as important to grid stability.

The energy security aspect of increased reliance on decentralized local renewable energy generation is enormous. Real time communications and control with the grid allows for renewable energy to become more significant, overcoming present maximum limitations to the implemention of residential-scale solar and wind power. Aside from the monetary value of the energy produced, it provides significant non-monetary value in energy security—there are ample examples from recent weather or other disasters. Even in the absence of major catastrophes, the cost of power interruptions can be significant and escalating.

4.2.3 Demand response – seconds

This form could be called automatic surge assist and could ultimately save as much money as demand response. Every power plant has some maximum capability. If the loads exceed this limit, then the frequency and voltage drops. When such changes occur the current drawn by inductive motors increases dramatically making the voltage drop even more thus aggravating the problem. Since about 40% of the loads on the grid may be inductive motors, this effect could be enough to collapse the grid—as happens with many power failures. To guard against this, the grid must always operate significantly below this "red line" to avoid collapse.

Inductive motors are physical machines with inertia so this surge assist process takes several seconds to a minute to unfold. The general move to higher efficiency may generally increase the percentage of loads that are inductive motors, as heating elements are replaced with heat pumps and incandescent lights are replaced with compact fluorescent lamps (CFLs). This change in lamps dramatically reduces the simple resistive portion of the load. The PMA could provide automatic surge assist from the energy stored in the batteries of uninterruptible power supply (UPS) systems and vehicle-based storage systems (e.g., PHEV, RV), or possibly new storage devices such as super-capacitors.[10] This entire surge assist event would normally occur within a minute or so and therefore the ultimate stored energy drain on the batteries would be negligible and have no effect on the life of the battery. Because the PMA detects and performs this operation locally, there is no need for communication with the grid.

Responding to surges may be the most expensive problem for electric utilities to address since they do not have enough time to bring on extra generation when this happens. Their only solution is to overdesign the main power plants that are in use every day and maintain “spinning reserves”. The cumulative effect of this surge assist could be as much as two times the supply, which relates directly to capital expenditures and dwarfs many other smart grid features that are presently in the spotlight. It also would avoid utility customer anxiety over “demand ratched” rate billing situations.

4.2.4 Demand response – milliseconds

Automatic power factor compensation operates on the millisecond time scale. Usually, this is often left out of smart grid discussions, but this is a very real issue. CFLs and Light-Emitting Diode (LED) lamps have a power factor of about 0.5 and computers often have a power factor of between 0.7 and 0.8. This problem causes the real usable power requirements of CLF and other reactive loads to be higher than their apparent power needs. Power factor compensation directly translates into not only more real usable power available from the power plant but also more real usable power delivered by the power lines and transformers in the distribution system. Transmission losses are becoming a more significant issue with the proliferation of low power-factor devices.[11]

Even if the utility compensated for the power factor at the power plant or at major power distribution centers, it would not provide any help on the distribution lines and local transformers. The PMA could incorporate this feature into a UPS system and renewable energy distributed generation systems in homes and offices at a scale that could fully compensate for problem power factor devices locally. This form of DR is clearly out of the realm of effective high-speed communications and needs to be handled locally by an automatic means. It not only could save the grid companies operating and infrastructure cost, but it improves the wave-shape of the AC power delivered by the grid by eliminating local distortions, electrical noise, and electromagnetic emissions.

4.3 General power management features and options

Following are some of the specific power management features and options that might be used to implement the above forms of DR using a Transverter or other appropriate Power Manager device, coordinated by a gateway and an appropriate PMA.

4.3.1 Delayed load application and soft-starting

When recovering or restarting after a power outage, a number of inductive motors may attempt to start simultaneously and present a load several times the normal operating load. The PMA can delay or sequence the startup of these loads—or “soft-start”—to greatly reduce the demands on the system. If the power manager has been operating certain critical loads from battery power, it could gradually or sequentially shift each load back to the grid power when the grid is able to support it, and then gradually return the battery charging load to the grid or other source.

4.3.2 T13X smart load controller

The T13X smart load controller is the part of the Transverter system that manages programmable delays of the larger loads so that the grid or generator has time to start all of the hard-connected loads and stabilize before these loads are selectively added. This process allows the same microgrid or nanogrid generator to operate with perhaps half the capacity that might otherwise be required. When combined with the communication ability of the gateway, the nanogrid could coordinate with other nanogrids in a local microgrid configuration to dynamically cycle large loads among nanogrids to reduce the aggregate load on the microgrid or on the grid as a whole.

4.3.3 Integrated renewable energy

Each Power Managersystem could integrate solar, windmills, fuel cells, or other sources automatically. Such integration could not only reduce the load on a grid but could contribute power to the grid. With many homes or nanogrids employing significant renewable energy sources, the requirements for grid or microgrid generation could be significantly reduced or eliminated.

4.3.4 Community energy storage

Each Power Managersystem could be equipped with a battery bank and could then serve to smooth out each individual system's power draw from the local grid, or contribute power to the grid when needed according to rules set by the user. This feature combined with renewable generating sources could reduce (or even eliminate) demands on grid generation. With individual Transverters in a community microgrid able to communicate via their gateways, a community PMA could coordinate load, storage, and generation resources within the community and reduce or eliminate the importation of power from the regional grid, or could even supply power to the regional grid.

This arrangement would allow for 100% utilization of all available power, even when some homes were unoccupied (i.e., vacant homes might still produce solar power or provide battery storage). A variation of this arrangement would be when the grid generation was only supplied during certain peak hours. The cost of batteries is projected to drop significantly over then next few years and electric vehicles or RVs may be parked in garages a significant part of the time.

4.3.5 DC sub-nanogrid

The need for a DC sub-nanogrid is growing, particularly with the migration to compact florescent lights which have a power factor of 0.5 and introduce substantial noise and harmonics to the current wave-shape taken from the AC grid. Computers and other electronics are similar with power factors of 0.6 to 0.7. LED lighting is an even more extreme case because LED's are essentially DC devices. It has been noted that photovoltaics and other renewable sources often produce low voltage DC that then requires AC conversion with only 42% efficiency, although the power may ultimately be delivered to a DC device.[12] Additionally, the lower the ratio of input to output voltage in power supplies, the more efficient the conversion process. Electronic devices usually operate on voltages below 12 or 5 volts. Nevertheless, there is considerable inertia with already owned and installed equipment, therefore an incremental, slow, gradual introduction of DC devices operating on a DC sub-nanogrid may be the only realistic course.

There are two fairly wide-spread DC grids already commonly in place: 12 VDC and 48 VDC. 12 VDC has been used by the automotive industry for years and may be in the process of migrating to the new 42 VDC standard for cars and trucks. This 42 volt migration has been advocated in order to introduce electronically controlled automotive engine valves (from a conventional camshaft), but higher currents would be required than would be feasible at 12 volts. Because the wire distances in cars are short, the 12 volt standard has worked fairly well, but homes and buildings require much longer distances and the wire sizes required for a 12 volt home sub-nanogrid are not practical. For any given amount of power, the higher the voltage, the lower the current and the smaller the wire sizes that are required. The telecom industry, including cellular sites and telephone switching offices, are already running on a 48 VDC standard. This is probably the obvious choice for DC sub-nanogrids.

With an upper limit of 50 volts there is no risk of electrocution (an important factor for a home environment). It is interesting to note that the safety/electrocution issue was central in the "War of the Currents" between AC and DC advocates during the earliest days of the electric grid. AC won out in spite of its hazards because it could be transmitted longer distances.

Each Transverter power module has two DC connections (that can be any value up to 50 VDC) and two AC connections (typically the AC loads and the AC grid). To transfer loads between power modules there is a 48 VDC bus that connects between one power module to the next. The DC connections are connected to devices like batteries, DC loads, solar panels, residential-sized wind generators, and fuel cells. Most installations would typically have at least two power modules installed which means a user would have at least four independently controlled DC connections that could be programmed to various purposes. Because of this shared 48 VDC bus, any source can power any load regardless of whether it is DC or AC. A user could use one of the DC connections to create a DC source of any voltage desired, but would occupy that DC connection. A preferred option might be to use the 48 VDC bus directly as a DC sub-nanogrid. In this manner, the user could have any mixture of batteries, solar panels, fuel cells, etc.—each at different voltages—each changing dynamically, with them all sharing power seamlessly.

4.3.6 Hybrid nanogrid

The Transverter system or similar Power Manger could be very useful without a DC sub-nanogrid. However, once installed, the 48 VDC sub-nanogrid is essentially in place and functioning, and all that is needed is to connect things to it as they become available. In addition, the T13X smart grid monitor and load controller uses Hall effect devices to measure the current on the six controlled load circuits so that they can be either AC or DC. DC lighting is the first obvious choice, but eventually electronics will be introduced. About 40% of the total grid loads are inductive motors and it is not likely that a high percentage of these would ever go to DC. Therefore a hybrid AC/DC nanogrid is likely to evolve gradually, at least for the next century.

Of course, everyone lives and works in houses and buildings which have elaborate networks of wires surrounding them that act as antennas for the current flowing through them. 60 or 50 Hz sine waves are create limited electromagnetic fields, but with CFL lighting, computers, switching power supplies, etc., there is are substantial high frequency harmonics carried through this elaborate mesh of antennas, with resulting interferencee and poorly understood health effects. This situation is avoidable by using a DC sub-nanogrid. Also more use of DC might ultimately be less expensive for product manufacturers (the cost of each light and electronic supply would be reduced), and might be more efficient and more reliable. Ultimately, what remains is AC wiring mainly powering inductive motors and some heating elements, all which involve pure sine wave power with no harmonics. The health considerations for an entire population living in the midst of all of these electromagnetic fields may be considerable.[13]

5. Conclusion

The conclusion drawn here is that the problem of how to implement the "smart grid" or how to incorporate DER into it may be simplified by taking a bottom up view and looking at the historical evolution of electricity itself. Such a view implies looking at the end point of the grid as a point of use, generation, and storage—as a microgrid or as a nanogrid in itself—and looking at the external grid as a storage device.

The term *demand response* is a utility grid-centric concept and embeds certain conventional assumptions about the structure of supply and demand that will likely be challenged. This term implies that it is the *demand* that is *responding* to the *supplier's* needs to balance the grid. In reality, a more appropriate term may be *demand/supply response*.

What is being suggested here is a basic paradigm shift to a distributed model of supply and demand focused on the end points rather than on the supplier. Such a revised model could offer enormous public benefits in terms of reliability, security, privacy,[14] environmental issues, grid stability and cost. A new model is needed because of inevitably and relentlessly increasing costs of carbon and conventional generation—and also the decreasing costs of alternative renewable and sustainable technologies (e.g., PV, computing, batteries)[15]. This evolution may even eliminate the need for a central grid in some situations.

One obvious problem may be that the conventional business model of the utility industry—particularly of investor-owned utilities (IOUs) and regulators—does not fit well with such a distributed model.[16] This institutional problem will require at least as much creativity as the technical problems, but in any case, the future is likely to be driven largely by economic forces.

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[1] A *gateway* is an interface between dissimilar networks.

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[15] It has been suggested that the cost of lithium-ion batteries may experience a dramatic decrease in the next five years (Charles Murray, “Analysts: Auto Industry Headed for EV Battery Glut.”

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