Powernet for Distributed Energy Resource Networks

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***Abstract*—We propose Powernet as an end-to-end open source technology for economically efficient, scalable and secure coordination of grid resources. It offers integrated hardware and software solutions that are judiciously divided between local embedded sensing, computing and control, which are networked with cloud-based high-level coordination for real-time optimal operations of not only centralized but also millions of distributed resources of various types. Our goal is to enable penetration of 50% or higher of intermittent renewables while minimizing the cost and address security and economical scalability challenges. In this paper we describe the basic concept behind Powernet and illustrate some components of the solution.**

I. Introduction

The electric power grid is undergoing a dramatic transformation. Electricity consumption worldwide is expected to grow 87% by 2035 including the addition of three billion new consumers without prior access. Intermittent renewables will be cheaper than centralized thermal power generation, taking the share of renewables beyond 50% of total generation. Supporting these transformations requires cost effective integration of significant amounts of storage, demand and supply flexibility. The grid edge provides a significant opportunity to achieve this goal as only 30% of the capacity of distribution networks is currently utilized. Yet, its current design is unsuitable [1]. Its architecture is centralized and hierarchical making it expensive to deploy, hard to modify and vulnerable. It assumes generation can be accurately controlled, demand is predictable and inflexible and energy cannot be stored. It utilizes limited data to make decisions and monitor performance. Absence of failsafe mechanisms has resulted in an unsafe network that can be disrupted by cyber and physical attacks. Lack of simple and automated compensation mechanisms has discouraged consumer participation.

Powernet is an end-to-end open source technology for economically efficient, scalable and secure coordination of consumer-side resources that addresses these issues. Powernet enables plug-and-play integration of distributed generation (solar, combined heat-power, diesel), storage and demand response (FIg. 1). It has a flexible architecture that supports bi-directional power flow and automates real-time operations via networked distributed computing. Powernet implements

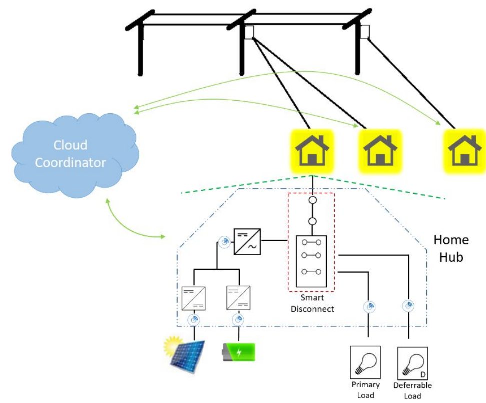

Fig. 1. Powernet's deployment within the legacy grid.

mechanisms ensuring efficient power sharing among consumers while coordinating them to provide aggregate services to the grid. The system is adaptable and robust to variations in consumption patterns, weather and grid conditions by relying on real-time measurements and learning. It minimizes information exchange and has built in failsafe and security mechanisms. Standardization, safety and stability are ensured by a low cost electronic interface that can connect to the various components. The whole system is modular so components from algorithms to power interfaces can be replaced as improvements are made.

The most closely related literature to Powernet is in smart micrographs for distribution networks ([2], [3], [4]). Several authors (e.g. [5], [6], [7]) have investigated the control, optimization and coordination of microgrid networks. Local management of DC networks[8] and solar inverters have been investigated [9]. In constrast, Powernet implements a solution that *co-designs* power hardware, software and algorithms to coordinate smart homes *utilizing the cloud* to *ensure* stability and efficiency. Open source interfaces and protocols and multiple time-scale algorithms are designed to ensure the optimal partitioning of the intelligence . (computing, communication and storage) between distributed and centralized resources.

The remainder of the paper describes the elements of Powernet and demonstrates an implementation of some of its features to justify the chosen architecture.

II. Powernet System Requirements

Powernet is organized as a hierarchical system to minimize communications. In the lower level, a Home Hub (HH) provides a unified power interface to various devices within a home. The HH implements local control and optimization algorithms to follow hub set points while respecting consumer preferences and ensuring network stability. Real-time measurements from loads and devices are utilized to form a representation of the capabilities of the hub. This information is sent to the higher-level, Cloud Coordinator (CC), that computes optimal power flow set points for each home hub based on desired aggregate net load outputs. The coordinator utilizes grid operator signals (regulation reserves, ramp rates, market prices, etc.) and grid data (voltage, frequency, phase at distribution and transmission network) to determine the desired net load and the inputs to the optimal power flow solver. The lower level hierarchy operates at a second to millisecond timescale while the higher level executes on the minute to hours time scale. The system provides regulation on top of the optimal operations. Our goal is to meet the following requirements:

(1) *Efficiency* enabled by cost effective power sharing among individual homes.
(2) *Islanded operation* capability to support ad-hoc connectivity.
(3) *Distributed intelligence* to automatically and dynamically balance loads in real-time.
(4) *Safety and plug-and-play* for loads, distributed generators and storage.
(5) *Backward compatibility* with the legacy grid.
(6) *Security* from the bottom up for control, optimization and communications.
(7) *Scalability* from kW to GW so that infrastructure can grow with individual needs and geographic expansion.
(8) *Coordination* to support transparent aggregate services to the grid (e.g. power regulation).
(9) *Fairness* by ensuring Quality of Service guarantees and fairness to consumers.
(10) *Economic viability* by supporting multiple services from cost-minimization to net load regulation services, voltage regulation and ramp following services.

III. Physical and Software Architecture

In this section we present Powernet's approach in addressing each of requirements (1)-(10). Powernet considers homes connected via their HHs to the software coordination platform, CC, implemented in the cloud. The system integrates physical systems through software application and user-driven functional components, each contributing to the overall goal to optimally, scalably and securely coordinate its resources. While HHs consist of both physical and software components, CC's functionality is software defined.

The system functionality can be organized into logical layers:

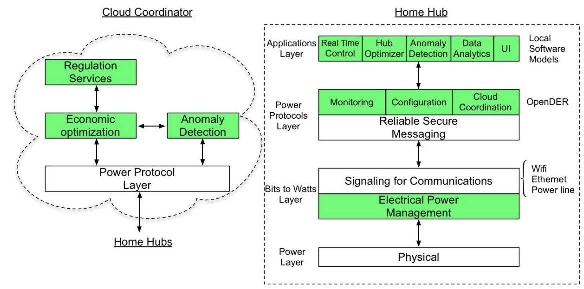

Fig. 2. Logical layering of required functionalities.

1) *Power*
   - plugs and enclosures to assure plug & play functionality between devices;
2) *Bits to Watts*
   - defines electrical behavior of the power conversion electronics for HHs (incorporates voltage, current, frequency interaction under various fault conditions);
   - stability and safety;
   - real-time control;
   - communication medium;
3) *Power Protocol*
   - networking (naming, routing, authentication and encryption);
   - Powernet protocol (HH configurations, monitoring, cloud coordination and optimization);
4) *Applications*
   - global power balance;
   - anomaly detection (safety and resilience);
   - user interface (applies only to HHs).

A. Home Hub

The end-user benefits of having HH capabilities are:

- Lower electricity bill:
  1) through locally optimized scheduling to take advantage of data-driven, user consumption patterns, installed appliances, storage and generation,
  2) through globally optimal coordination of DERs among HH owners.
- Automatically and seamlessly deals with utility outages: manages loads as required when power supply is limited.
- Coordinates large loads (e.g. EV charging, AC) so as not to exceed HH's limits.
- Provides easy monitoring and control (cloud-based and/or local).
- Enhances safety.
- Provides automatic analysis of usage patterns and home loads, recommendations on energy savings and avoiding load failures.
- Integrates seamlessly with a home control solution and/or smart appliances.

- Is ready to provide utility-side services via global coordination with the a single or multiple CCs (regulation services, demand response, VAR control, etc).
- Can cover both grid-tied and off-grid installations.

Next, we describe HH's functionalities in more detail.

1) HH's physical component: Each home in Powernet can have generators, loads and storage. These devices are connected to the physical HH consisting of: (i) safe DC power ports and power electronics for connecting storage, generation and loads; (ii) *smart disconnect* panel that enables connect/disconnect control of the home and individual loads; (iii) communication-based device control; (iv) local sensors measuring voltage, current and power at home and device level.

One of the key functionalities captured by *Power* and *Bits to Watts* layers is *safety*. It incorporates capability to automatically deal with grid outages, both short (hours) and long-term (days). Dealing with outages requires a switch-over of primary supply from the grid to an on-premise supply (such as battery or a genset). Disconnect from the grid is required as per anti-islanding regulations (UL 1741, IEEE 1547). Switch-over to alternate supply has more choices, arranged in decreasing order of desirability: (i) uninterrupted power flow (home devices cannot tell that there was a switchover); (ii) briefly interrupted power flow, a few seconds or less (home devices see a power interruption); and (iii) manual switch-over (power restored to home only after action by user). Furthermore, safety is enhanced by the provision of faster, smart, circuit breakers, with integrated ground and arc fault detection for every breaker. Remote control of all load circuits also allows for the shut-off of entire circuits when they are not needed, which might also enhance overall safety. HH's required safety and control features incorporate: (i) remote operability of individual branch circuits, and (ii) monitoring of current at individual branch circuits.

Apart from the on/off control of individual circuits, which is sufficient for curtailing loads and shaping power flow to match supply, HH is capable of a much smoother interaction with loads with finer grained control (e.g. per outlet) or smarter control of appliances (e.g. allow fridge to remain powered, but disable the compressor cycle from kicking in).

2) HH's software component: The key functionalities include: (i) data collection and processing for the purposes of learning user preferences, information sharing with CC, and data-driven anomaly detection, (ii) optimization and control to ensure cost-effective and real-time balancing of local and shared resources and (iii) UI for consumers.

HH has a connection to the Internet and acts as a client to a *back-end system in the cloud*. The back-end system, in turn, supports authenticated access for users to monitor and control their system from web applications and mobile devices. The back-end system is also responsible (if enabled by the user) to check up on the health of the system and provide historical information of power flow and system events. No critical function of the HH must rely on connection to the cloud, though. In fact, cloud connection may not be desirable to some users, so basic system monitoring and control functions should be available without requiring cloud access of the system.

Having access to round-the-clock circuit-level power information in the home allows additional analysis and alert functions to be implemented. Examples are giving recommendations on electrical rate choices, opportunities for energy savings, alerting on abnormal conditions.

Utility-side services: HH can provide specific shaping of active and reactive power draw, and respond to signals for load curtailment or increased supply that it receives from the CC it is registered with.

HH needs to be able to work completely unattended for long periods of time; set it up and it just works. However, there is also the ability to monitor and control HH via one of three levels of user interfaces: (i) local panel: there is a local display on the HH. It is strictly meant for local interaction at a very low level, such as during configuration or for getting error messages when all comms are down; (ii) home network: there is likely an in-home dedicated control panel. In addition, we can support any device (such as a tablet) connected to the home network. This should work even for those users who are unwilling to send their data to the cloud, or open control to the cloud; (iii) cloud services: the richest monitoring and control options are available via the cloud. Analysis services are also available this way. The cloud services are accessed via web or mobile clients.

HH's *optimization* computes the locally optimal time schedule of nominal set points for household loads, generators and storage. It uses the globally optimal net load received from CC and voltage time schedule, and runs the finer grained optimization taking into account the properties of home devices. The cost optimization takes as inputs specified load priorities, generation and battery effective costs. The optimization constraints consist of operational, dynamic and user-defined QoS requirements:

$$\text{minimize}_{\boldsymbol{P}_l,\boldsymbol{P}_g,\boldsymbol{P}_s}$$

$$\mathbf{E}\left[\sum_{l\in\text{Loads}} Cost^{(l)}(\boldsymbol{P}_l) + \sum_{g\in\text{Gen}} Cost^{(g)}(\boldsymbol{P}_g) + \sum_{s\in\text{Stor}} Cost(\boldsymbol{P}_s)\right]$$

subject to

Power flow constraints, $\forall t$**.**

Device operational constraints and forecasts, $\forall t, l, g, s$**.**

Local storage operational constraints, $\forall t, s$**.**

Net load constraints $\forall t$ **(from CC).**

The result of the optimization is the power dispatch and the corresponding time series of optimal duals (prices) for each of the potential power sources (e.g. solar panel, genset, battery) that map into generation and load priorities, that are used to effectively handle unpredictable changes in load and generation within each home in real-time.

More specifically, the selected control mechanism implemented within each HH: (i) needs a way for the local optimizer to specify the load-sharing behavior for the complete space of

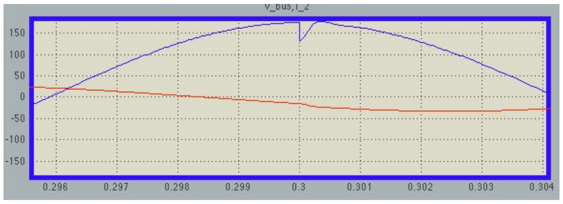

Fig. 3. The data shows how the local impedance controller manages substantial reactive loads, without Q compensator in the system.

Fig. 4. Simulation trace showing synchronization and hot-connect at $t = 0.03$ seconds.

possible perturbations, (ii) needs a control scheme to continue working without updated information from the optimizer for an extended period of time, even if suboptimal.

HH's real-time interaction with the grid: HH's inverter controls need to ensure stable and controlled power sharing in the network of registered HHs, and non-HH capable homes connected to the same feeder (legacy grid): (i) fast and smooth transition to a new operating regime (as prescribed by the CC), (ii) fast and slow ramp devices attached HH can respond in a stable manner, (iii) controlled (limited) current surges in transient regimes (smooth plug-and-play). Figure 3 shows the simulation results from the perturbation in reactive load at $t = 0.3$ seconds. Note that voltage adaptation to load change appears to take about $\frac{1}{3}$ milliseconds.

Figure 4 shows a smooth correction for long-term frequency error in phase deviation.

B. Cloud Coordinator

CC consists of functionalities that allow (a) registering and managing the HH, (b) anomaly detection and (c) controls (optimization and real-time operations). Registration and management are standard, and include managing synchronization of HH and CC. Anomaly detection as described in Section 2.1.6., outputs a reliability rating for each HH that is used in the optimization.

The *optimization component of the CC* solves a multi-period (dynamic) economic optimization that outputs the nominal net load set points for each home. In addition, there is a mechanism for the fast response to the regulation signals using the optimal duals (prices) at the current setpoint.

Multi-period economic optimization minimizes the system-wide economic cost over a finite decision horizon with T periods (minutes) given homes' aggregate cost functions, power demand forecasts, shared storage parameters and costs reported to the CC. The optimization is resolved every minute as in rolling horizon control, with the updated information collected from the homes. When there is a regulation request, the optimization includes an additional term in the objective function, penalizing the deviation from the regulation signal. In addition, it also includes a chance constraint (or other forms of risk constraints), enforcing that the probability of not meeting the regulation signal is less than the provided tolerance (99%). We denominate this the ROPF (robust OPF). In the base case of the CC implementation, we optimize against the predicted scenario for the future periods, i.e. we use Model Predictive Control (see e.g. [10]) to cope with the uncertainty due to renewable generation and demand.

At the center of this multi-period economic optimization is an efficient approach to solve deterministic optimal power flow (OPF) problems based on sequential convex programming. In general, the OPFs resulting from the multi-period optimization solve for the cost-optimal complex voltages and net complex powers, and are not convex optimization problems. Its commonly used representation is a semidefinite program (SDP) [11], which fails to capture many of the intrinsic properties of the optimization at the CC. Our approach consists of solving a sequence of convex programs, original problem's relaxations, that provably converges to a locally optimal OPF solution for any network topology, and in a very few iterations. Preliminary tests on IEEE systems [15] show that the method results in small duality gaps and thus good practical power flow solutions are expected.

Using the approach above, CC computes the minute level global power balancing trajectory for the whole Powernet system. The optimization at HHs is triggered by a new net load's time schedule sent by the CC, or parametric and configuration changes within the specific home introduced by its consumer. This two-level optimization preserves the home's privacy, since only net load curves and available storage are shared with the CC. When tracking regulation signals, CC's optimization incorporates the corresponding penalties and forecasted demand, resulting in a modified control of HHs' net loads and storage. Appropriate payments incentivize the consumer to share for these purposes. In addition to computing the optimal long-term trajectory (net load) for each registered HH, CC defines their operating regime in the neighborhood of the nominal set point obtained from the CC's global optimization.

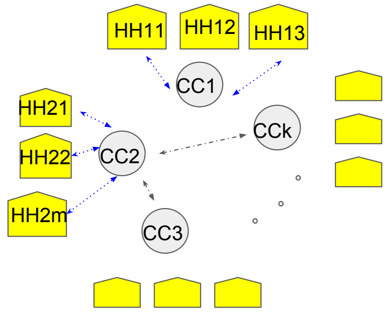

Fig. 5. Higher level coordination mechanisms among CCs.

C. System Integration and Scalability

The proposed Powernet's hybrid solution between the fully decentralized and fully centralized architectures meets all the system level requirements as outlined in Section II. The only way to decouple the fine-grained, end-user preferences, consumption patterns, and, at the same time, achieve benefits of the global coordination and control offered through the CCs services is through the customized user representation and optimized communication with higher level aggregators, CCs. Even though the current paper describes the functionalities of HHs attached to a single CC, one can think of a higher-level, economically incentivized, coordination mechanisms among different CCs.

D. Timing Considerations

There are two ways of solving the multi-period optimization at CC: distributed and centralized. The distributed implementation assumes that (i) the objective function is separable, (ii) the original problem is convex, and (iii) part of the optimization logic is embedded locally at each home ("slaves"). Coordination mechanisms utilized by CC ("master") make sure that the global, power flow constraints, are not violated, and that the duals (currently negotiated prices) get updated (see [12]). These schemes have desirable properties, such as computational simplicity of local optimization problems, preserved privacy of local information, and system scalability. However, our experimentation using the hardware-in-the-loop and basic communication protocols to implement negotiation mechanisms, exhibited substantial communication delays, implying slower global convergence of these algorithms, and therefore, their infeasibility in real systems. Therefore, we select the centralized approach in solving the global ROPF at CC. To test the time and memory requirements, we simulate the system consisting of a large number of homes. We assume that each home has a storage device with the specified efficiency, storage capacity and price, as well as specified net demands and corresponding prices. Half of them are assumed to have PV panels.

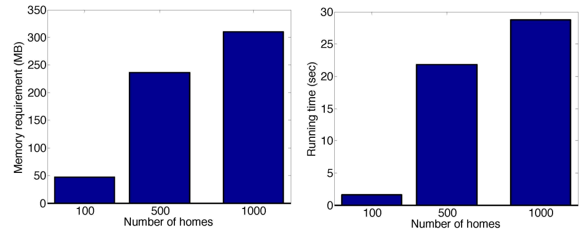

Fig. 6. Running time and memory requirements for the CC's optimization with a large number of HHs.

IV. Conclusion

In this paper we propose the power interface, software and hardware components of Powernet: a cloud enabled coordination system for distributed energy resources for residential and commercial consumers. The main innovations are the partitioning of centralization and decentralization, the integrated system design and the plug and play implementation that ensures various important system properties including efficiency and stability. Open source protocols enable participation of future devices. In future work we will explore how multiple grid services can be provided in such platform, design more extensive experimental validation of this system and explore novel algorithms at multiple time scales, payment mechanisms and planning for Powernet enabled systems.

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