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Smart Grids with Intelligent Periphery: An Architecture for the Energy Internet

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ABSTRACT A future smart grid must fulfill the vision of the Energy Internet in which millions of people produce their own energy from renewables in their homes, offices, and factories and share it with each other. Electric vehicles and local energy storage will be widely deployed. Internet technology will be utilized to transform the power grid into an energy-sharing inter-grid. To prepare for the future, a smart grid with intelligent periphery, or smart GRIP, is proposed. The building blocks of GRIP architecture are called clusters and include an energy-management system (EMS)-controlled transmission grid in the core and distribution grids, micro-grids, and smart buildings and homes on the periphery; all of which are hierarchically structured. The layered architecture of GRIP allows a seamless transition from the present to the future and plug-and-play interoperability. The basic functions of a cluster consist of ① dispatch, ② smoothing, and ③ mitigation. A risk-limiting dispatch methodology is presented; a new device, called the electric spring, is developed for smoothing out fluctuations in periphery clusters; and means to mitigate failures are discussed.

KEYWORDS smart grid, future grid, Energy Internet, energy-management system, integrating renewables, power system operation, power system control, distribution automation systems, demand-side management

1 Introduction

China's rapid transformation in the last 30 years from an underdeveloped country to the second largest economy of the world has lifted hundreds of millions of people out of poverty and brought prosperity to her people and the rest of the world. China's rise has inspired many others to follow. The 21st century will mark the "rise of the rest"—from Asia and South America to Africa. The path of China's development largely follows that of the West: The economic growth is driven by fossil-fuel energy and accompanied by the depletion of resources and degradation of the environment. The damage brought by environmental pollution has started to show up in China as the devastating long-term health and economic consequences of the development. China is the number one emitter of greenhouse gases (primarily carbon dioxide) that contribute to anthropogenic global climate change, a crisis that is leading to an existential threat to human civilization. India is on its way to become the number one greenhouse gas emitter in the next 20 years. The conventional path to economic development is not sustainable and is no longer an option. At the upcoming 2015 Climate Summit in Paris, world leaders are expected to declare Intended Nationally Determined Contributions to reduce greenhouse gas emission. Time is running out. This may be the last chance for humankind to limit global temperature rise to 2 °C above pre-industrial levels—the scientific consensus of the threshold to catastrophic and irreversible damage to the planet. The United Nations has resolved to develop the post-2015 Sustainable Development Goals in order to achieve global economic development without environmental damage (zero poverty/zero carbon).

The electric grid plays a central role in the chain of energy conversion from sources to useful activities that drive economic development. Sustainable development critically relies on a workable future grid to support it. A properly functioning future grid will be able to contribute to ① decarbonization of energy sources, ② efficiency improvement in conversion processes and end-uses, and ③ clean transportation.

- **Decarbonization of energy**: Future energy sources will have to transition from fossil fuels to renewables such as wind and solar power, and perhaps nuclear, in order to reduce carbon emission to the atmosphere. Nuclear generation is an established and often controversial technology whose integration to the grid does not change the status quo. Future grids must be operated in such a way as to facilitate greater extraction and utilization of renewable energy resources, which are intermittent and variable.
- **Efficiency improvement**: Electricity helps to decouple

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energy use from gross domestic product (GDP) and population growth, contributing to reducing carbon intensity (carbon emission per GDP). Future smart grids that apply advanced computer, communication, and Internet technologies will be able to significantly improve efficiency in all aspects of electricity generation, transmission, and utilization processes. End-use energy management helps energy to be used more efficiently through more intelligent management.

- **Clean transportation**: Transportation accounts for a quarter of total carbon emission in the US and other advanced countries—second only to electricity. Electric vehicles, coupled with decarbonized future grids, will help transform the existing transportation modes into clean and sustainable transportation.

Section 2 of this paper discusses what lies ahead in the future grid, or Energy Internet. In order to get a firm "grip" on the future, we propose the development of a smart grid with intelligent periphery, or smart GRIP, for the future. Section 3 lays out a layered architecture for smart GRIP that facilitates a seamless transformation from the present to the future. The building blocks of GRIP are called clusters. The basic functions of all clusters, large or small, are the same, consisting of ① dispatch, ② smoothing, and ③ mitigation. A risk-limiting dispatch methodology is proposed in Section 4 and a new device, called the electric spring, for smoothing out power and voltage fluctuations on the future grid is described in Section 5. Section 6 discusses ways to mitigate failure and concluding remarks are made in Section 7.

2 Future grids: The Energy Internet

The conventional electric grid evolved over the span of the 20th century. This was a different era in which the energy sources were primarily large-scale fossil-fuel power plants, augmented by large hydro and nuclear plants. The technologies for these resources favored economy of scale. A brief summary of the salient features of the conventional electric grid is listed below for later comparison with upcoming transformations.

(1) The suppliers, that is, the power companies, have the obligation to serve random load demands from consumers. In other words, loads are passive and uncontrollable.

(2) In an era of mechanical devices, an economic and reliability trade-off has led to the differences in the structures and operation of the high-voltage transmission grid and the low-voltage distribution grid.

(3) The lack of economically viable energy-storage technology (except for pumped storage where the geography allows it) obligates the system operator to strive for instantaneous power balance. A whole set of planning and operation functions are built around this main objective.

(4) The emergence of the energy-management system (EMS) in the 1970s brought intelligence into the transmission grid [1]. An EMS's real-time monitoring and control may cover several hundred generating and transmission substations using a centralized architecture. The EMS stretched the limit of the capability of the computer and communication technologies at the time.

(5) Uncertainties on the grid are manifested in ① load variations and ② equipment failures. Both can be handled adequately, albeit conservatively, using deterministic methodologies (i.e., reserve margins and N–1 contingencies).

Innovations in the improvement of efficiency and reliability of wind and solar power technologies in recent years are making renewable resources cost-competitive to conventional energy sources for electricity [2]. Megawatt-level on-shore wind turbines have become a mature and standard technology and are lower in levelized overall plant costs without government subsidy in increasingly number of locations. Technologies for offshore wind power are advancing. Solar photovoltaics (PVs) are on a fast track of technological development [3]. Innovations in material science research have led to newer generations of PV cells, such as thin-film, multi-junction, organic, and quantum-dot cells, that promise much higher efficiency and lower cost in the future. Embedded power-electronics enabled power optimizers in PV modules further improve the overall power output and efficiency of the system. The prices of PV modules have reduced to one-fifth and those of PV systems to one-third within the past six years.

Energy-storage technology is the key to the future success of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). Grid-connected energy storage is also a valuable component that provides flexibility in instantaneous supply-demand balance in the presence of intermittent and variable renewables. Rapid innovations have greatly changed the performance of several conventional energy-storage technologies and introduced some new and novel ones. Grid-level rechargeable batteries, including lithium-ion, flow, and other types, are steadily overcoming their traditional barriers of small capacity and high cost. Research and development in flywheel, compressed air, thermal (molten salts), and hydrogen storage systems are making great progress. In addition to physical storage devices, great potential lies in the exploitation of end-use side energy storage for the grid. For example, energy-demand management of water heaters and air-conditioning cycling utilizes the thermal energy stored in water tanks and buildings at consumer premises in exchange for electricity. Smart vehicle charging and discharging (or vehicle-to-grid, V2G) technology utilizes electrochemical energy stored in the batteries of EVs/PHEVs to act as energy storage for the grid. These "virtual energy-storage systems," when properly managed in the future grid, can provide a large quantity of cost-efficient power in both directions to the grid.

Since 2010, the world has added more solar PVs than in the previous four decades. Renewable generation led by wind and followed by hydro and solar power accounts for a major share of new generation investment worldwide. Wind and solar power generation in the world today are around 400 GW and 200 GW, respectively. By 2050, according to the International Energy Agency (IEA), wind may supply 30% of global electricity and solar 15%–20% [4]. The IEA's roadmap calls for governments to encourage the supply of half of the vehicle fleet by EVs and PHEVs by 2050 when the grid will be mostly powered by renewables. The power of innovations must be unleashed on the world. While advancements are continuous in energy technologies, innovation is now needed on the system in order to enable the efficient development and utilization of new technologies. Economic and policy aspects of the electric energy system, including well-designed markets, efficient pricing, and appropriate regulatory frameworks, need to be developed. Market, pricing, and government regulation depend on how the grid is operated. Innovation in smart grid operation is the first step toward ensuring that the smart grid of the future will receive and distribute electricity from renewables and V2G to end-use with maximal efficiency and utilization. Advances in information and Internet technologies are ready to step in to contribute to necessary innovations.

The composition of the future grid will be fundamentally different than that of the conventional electric grid. Solar PVs and battery storage are technologies that, unlike conventional ones, do not have economy of scale. The growth of self-generation and consumption due to a combination of decentralized PV generation, residential electricity storage, and EVs, would fundamentally transform the grid in the next 10–20 years. Rifkin [5] proclaimed that the human society must advance to a new era where renewable energies and Internet technology merge to create a powerful new infrastructure that he calls the Third Industrial Revolution. In this vision, hundreds of millions of people will produce their own green energy from renewables in their homes, offices, and factories and share it with others through an "Energy Internet," just as we now create and share information online. Energy will be locally stored in every building and throughout the infrastructure by deploying various energy-storage technologies. Moreover, the transport fleet will be transitioned to electric and fuel-cell vehicles. To realize this vision, Internet technology must be utilized to transform the power grid into an energy-sharing inter-grid. When energy is produced by and shared with millions of ordinary people, the traditional pyramid-like social structure from top to bottom must give way to side-to-side lateral structure. The lateral social structure extends the sharing of information to sharing of energy, and to sharing of benefits and responsibility—leading the world into a collaborative era with profound implications on how we orchestrate the entirety of human life (economic, political, and social) in the new century.

The idea of an "Energy Internet" is consistent with our notion of the future grid. The characteristics of the future grid will be profoundly different from the grid existing today. From the point of view of grid operation, four fundamental differences between the current and the future grids are noted below.

(1) **Loads become controllable**: End-use EMSs, including demand-side response of residential water heaters, air-conditioning, and smart appliances, as well as building EMSs, are making loads controllable. Battery and other energy-storage systems, as well as V2G systems, further contribute to active controllable loads.

(2) **Both generation and load demand are stochastic**: The output of wind and solar power generation, depending on wind speed and solar radiation, is intermittent and highly variable. Variability of the load demand will be heightened by the presence of end-use energy management, storage management, and V2G technology.

(3) **Massive amount of sources and intelligence are distributed on the grid**: Dispersed energy resources (DERs), including renewable energy and energy storage in homes, buildings, and factories, will be massive in number. Smart meters and advanced metering infrastructure (AMI) are adding intelligence to the grid. In the age of the "Internet of Things," these and other new components (e.g., smart appliances, end-use energy management, EV, and V2G) on the grid will all be embedded with intelligence and communication capability.

(4) **Distribution grids will be like transmission grids today—similar for buildings and homes**: DER will be all over the distribution grid and power will no longer flow in one direction from the substation down; rather, it will flow in whichever direction dictated by the DER generation. With bi-directional power flow, the distribution grid must be operated and managed in the same way as the transmission system today. The same goes for smart homes and smart buildings, which will have their own on-site generation and control.

3 GRIP architecture

Accommodating an increasing number of new entrants to the grid—dispersed renewables, demand-side management systems, and so forth—into the present operating paradigm is already a growing pain. Operators are concerned about unobservable generation from decentralized renewables and unpredictable response from the demand side. Future trends have just begun. The traditional centralized control paradigm can handle hundreds or even a few thousand monitoring and control points, but not the millions of homes, buildings, and factories of the Energy Internet. According to the existing paradigm, the administrative, informational, and technical relationships among the new and old entities involved in a smart grid can only be described as "emerging structural chaos" [6]. The Chinese saying "shaving your foot in order to fit the shoe" is the best description of the current approach to the problem. The grid is undergoing unprecedented transformation. Fundamental changes require a fundamentally different new operating paradigm.

In response to these fundamental changes, we propose a smart grid with intelligent periphery, or smart GRIP, for the future [7]. GRIP is built on the three pillars described below.

(1) **Empowering the periphery**: Uncertainties in both generation and load demand pose the greatest challenge to the operation of the future grid. The proliferation of massive dispersed renewables and end-user EMSs brings greater uncertainty in supply and demand on the periphery of the grid, that is, distribution grids, micro-grids, factories, buildings, and homes. We believe that the solution to tackling this problem lies in the placement of the management of uncertainty close to its source, that is, the periphery. The periphery of the future grid must be empowered to share the operational

responsibility of the grid in the era of collaboration.

(2) **Abstracting commonality**: Future distribution systems, as well as buildings, factories, and homes, will all be like the transmission system (or the micro-grid) today with local generation and bi-directional power flows. The difference between the core (the transmission grid with real-time EMS) and the periphery (distribution grids, micro-grids, buildings, factories, and homes) is disappearing. Seeking commonality between the core and the periphery is the key to a uniform approach to a future operating paradigm.

(3) **Layered architecture**: The grid will not change overnight. Today's core-centric grid will evolve rapidly but continuously into tomorrow's periphery-empowered grid. Architecture for the future grid, or the Energy Internet, must take into account the legacy grid and its evolution into the future. The legacy system will still last for some time. The evolution will take place in a varying pace for different grids as a function of local rates of adopting new technologies. A layered architecture [8] that is suitable for seamless transition and plug-and-play interoperability is needed.

3.1 Clusters

As pointed out in Section 2, future smart homes, equipped with smart meters capable of controlling rooftop PV generation, on-site battery storage, demand-side and V2G management systems, and smart appliances, are no different from an EMS-operated power grid. Similarly, distribution grids and micro-grids on the periphery will all have intelligence and controllable generation and loads. They will be the building blocks, or cells, of the proposed GRIP architecture and will be called "clusters." A cluster has ① generation and/or load and ② intelligence to control and communicate. A cluster is an object abstraction of the fundamentals of power system operation; a concept that will be elaborated on in Section 3.3. Smart homes, buildings, factories, micro-grids, and distribution grids (represented by the substations from which they emanate) on the periphery are all clusters. Any "control area" of the core transmission grid is also a cluster. Clusters are thus interconnected and hierarchically structured (Section 3.2). A core transmission grid cluster contains many clusters of distribution grids, each of which contains clusters of micro-grids, factories, and homes. A micro-gird cluster may contain several clusters of smart homes. The internal working of a cluster is encapsulated behind a well-defined interface; this concept will be discussed in Section 3.3.

The distributed nature of renewable energies in the Energy Internet brought by the Third Industrial Revolution necessitates collaborative rather than centralized or hierarchical command and control mechanisms. Collaborative behavior will lead to a more distributed sharing of the benefit generated. Clusters will work together to ensure the maximal and most efficient utilization of renewables. Mutual interest, pursued jointly, is the best route to sustainable economic development. Clusters will be required to share the operational responsibility of maintaining the instantaneous power balance of the system by scheduling and maintaining individual net power balances (Section 3.3).

3.2 Architecture

Figure 1 illustrates the skeleton of GRIP architecture. The clusters are hierarchically structured. A core transmission grid cluster contains many substations, micro-grids, and perhaps factories; each of these is a cluster on its own. A cluster composed of a substation and the associated distribution grid lies within a large core cluster and contains several smaller clusters of micro-grids, buildings, and homes. A micro-grid cluster located inside a substation cluster may contain several clusters of smart homes and buildings. Clusters have intelligence to access real-time data from the smart grid (information), to analyze the state of the cluster and necessary actions (computation), and to carry out operational decisions (control).

The basic functions of all clusters are the same and are carried out by means of "applications." A rudimentary three-layer architecture is suggested here as a start. At the bottom is the device layer, which is an abstraction of the devices that interface between the cyber and physical systems. Smart sensors and actuators belong to this layer. A higher layer is called the service layer, which employs the devices to perform specific services. For example, a communication service may transmit data collected from sensors, a computation service may act on the data to extract information, and another computation service may perform analytics to assist decision-making. At the top is the application layer, which utilizes the services provided below to carry out functions that are required by the cluster. These functions include the scheduling of generation and management of load and will be elaborated on in the next sub-section. Protocols and standards for each layer and the interface between the layers must be further developed in order to achieve plug-and-play interoperability. Protocols and standards for GRIP should be compatible with existing ones, such as the Smart Grid Architecture Model, IEC and IEEE standards, and so forth.

The level of sophistication of applications of different types of clusters will be different according to their composition and requirements. Even for clusters of the same type, such as smart homes, different applications may be used depending on how well the owners want to manage their homes, as long as protocols and standards are followed.

3.3 Functions

The basic functions of a cluster are abstracted from the funda-

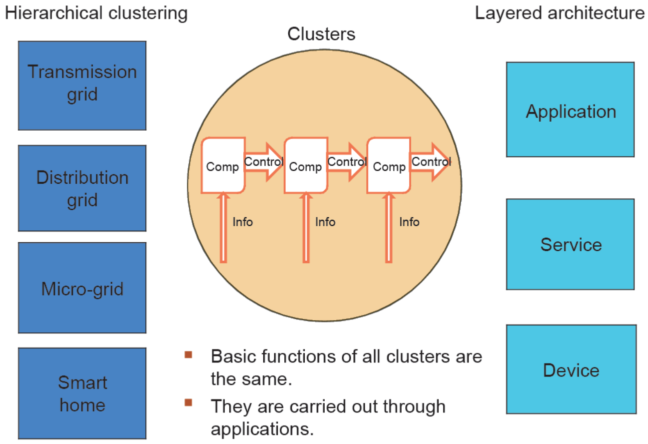


Figure 1. GRIP architecture.

mentals of power system operation within an interconnection. The interconnected power system was greatly expanded in the second quarter of the last century. That was a time when many ground-breaking power systems engineers developed the "protocols" of the present-day paradigm of power system operation. The idea of a "control area," along with the "standards" for interconnection was developed [9]. A control area is obligated to maintain its external exchange schedules. The obligation must be met even when a major disturbance within the control area happens. How a control area operates to meet its obligation is its own business. In modern terminology, a control area must follow the definition of the interface within the interconnection and encapsulates its internal workings. A control area is the basic unit of a power system in an interconnection and must maintain its instantaneous net power balance, including the exchange schedule. This is accomplished through three steps: ① scheduling and dispatch generation to maintain net power balance, ② frequency control using governors and voltage control using exciters in synchronous generators to smooth out fluctuations of imbalance, and ③ shedding load in an emergency when there is insufficient generation to meet the load.

Clusters in GRIP are defined as power systems that are capable of intelligently managing their own generation and load. Clusters on the periphery must function like power systems and be empowered to contribute to the operation of the overall system. They must bear their share of responsibility in the maintenance of the instantaneous power balance of the whole system. Clusters are required to externally schedule, commit, and maintain their exchange schedules. This means that a cluster schedules its purchase and selling of electricity and informs the cluster above it of that commitment. In operation, a cluster must internally manage its own power generation and consumption in order to maintain its net power balance, taking into account its commitment of external power exchange. For example, the scheduled power exchange for a smart-home cluster may be the amount of consumption at different times of the day. The home cluster must inform the distribution grid cluster to which it belongs of its consumption schedule ahead of time and commit to it. The exchange may take place in an electricity market and sequential scheduling (i.e., updated adjustments) is possible.

The basic functions of a cluster consist of three steps, similar to those of a control area:

(1) Dispatch of generation/load to maintain net power balance;
(2) Local feedback control to smooth out fluctuations; and
(3) Mitigation of failures by cutting generation/load.

These three basic functions will be elaborated on in the next three sections. Though our immediate focus is on clusters on the periphery, where revolutionary changes are happening, the core transmission grid is also a cluster and the same methodology must apply to it. Of the three functions, the core is affected most by the changes in the dispatch philosophy. The legacy system must adapt to the changes and be able to evolve seamlessly into the new paradigm. Our design of the risk-limiting dispatch methodology (Section 4) has taken this need for evolution into consideration. A local feedback-control device, called the electric spring, and its applications to periphery clusters in order to smooth out fluctuations of power imbalances have been developed (Section 5). Section 6 briefly discusses means of mitigating failures.

4 Risk-limiting dispatch

The proposed risk-limiting dispatch (RLD) [10, 11] is built on a stochastic approach. It differs from the conventional dispatch methodology in three aspects, as described below.

4.1 Risk

When generation and load are random (stochastic) variables, there is always a probability that generation and load will not be exactly matched. The concept of risk, i.e., the risk of failing to maintain a net power balance in a cluster, must be considered. The objective in operation is to minimize this risk. The assessment and management of risks have been a major endeavor in modern banking and financial sectors, resulting in the development of sophisticated measures and methods [12]. Here, for purpose of illustration, a simple risk measure is presented.

Consider a cluster whose objective is to balance the supply $s(t)$ and demand $d(t)$ at the operating point t, so that $s(t) = d(t)$. When the demand $d(t)$ is stochastic and has a probability distribution P, $P\{s(t) \neq d(t)\} = 1$. However, practically the supply side always has the ability to cut generation instantly by a certain amount ε. Hence the failure to maintain a net supply-demand balance is described by the event $\{d(t) > s(t)\}$ or $\{d(t) < s(t) - \varepsilon\}$. A simple measure of risk is the probability of failure, $P\{d(t) > s(t)\}$ and $P\{d(t) < s(t) - \varepsilon\}$. The objective is to limit this risk to an acceptable level, that is, by requiring

$$P\left\{d(t) > s(t)\right\} < \alpha \quad \text{and} \quad P\left\{d(t) < s(t) - \varepsilon\right\} < \beta \tag{1}$$

where α and β are any small numbers, for example, 0.1% or 0.01%, that are specified by the user.

4.2 Supply and demand

The conventional dispatch philosophy of "generation following load" is based on the facts that ① generation is largely deterministic and controllable and ② the load is variable and not controllable. Generation and load are becoming indistinguishable as generation becomes more stochastic and load more controllable. In the new paradigm, we separate the deterministic and stochastic parts of the generation $G(t)$ and the load $L(t)$ into

$$\begin{aligned} G(t) &= GD(t) + GS(t) \\ L(t) &= LD(t) + LS(t) \end{aligned} \tag{2}$$

where the stochastic $GS(t)$ includes renewable generation such as wind or solar power; the deterministic $LD(t)$ includes controllable load such as demand-side management. The net balance of generation and load $G(t) = L(t)$ can be rearranged as follows:

$$GD(t) - LD(t) = LS(t) - GS(t) \tag{3}$$

Let us call the left side, the deterministic component of generation/load, the net supply $s(t)$ and the right side, the stochastic component, the net demand $d(t)$. The net supply is deterministic and partly controllable and the net demand is stochastic. The RLD dispatches the controllable part of the net supply to follow the stochastic net demand.

4.3 Decision process

The key to managing uncertainty in the future grid lies on the ability of the smart grid, equipped with sensors and communications, to continuously provide timely information about the grid. Typically the uncertainty on both generation and load decreases as the time nears the real-time and the decrease follows a sharp exponential decay. For example, the error in a day-ahead wind forecast could be as large as 30% whereas the error in the forecast made minutes ahead would shrink to almost zero. In other words, the probability distributions of the net demand in a cluster, when updated from the information provided by the smart grid, get sharper and sharper. We therefore adopt the framework of a multi-stage stochastic decision process for the RLD (Figure 2). The stages could correspond to the dispatch decision points under the structure of an electricity market, e.g., a sequence of day-ahead market, hour-ahead market, and minute-ahead real-time market.

Before presenting the mathematical formulation of the RLD, some notations need to be established. The net demand $d(t)$ is stochastic and has probability distributions that are updated at each stage from the information Y_i provided by the smart grid, denoted by $P_i\{d|Y_i\}$, at stage i. The objective of the dispatch, J, must be defined; for example, as the minimization of the expected total cost. The objective function J, in general, is a function of the dispatch decisions of net supply $s(k_1, ..., k_i)$, $i = 1, 2, \dots, m$, that are made at all stages.

The RLD, represented by π in Figure 2, is formulated as:

- Select controllable net generation, $s(k_1, ..., k_i)$, $i = 1, 2, \dots, m$, i.e., $s(k_1)$, $s(k_1, k_2)$, $s(k_1, k_2, k_3)$, …
- To optimize the objective function J,
- Subject to the risk-limiting constraints, e.g., $P_m\{d(t) > s(t)|Y_m\} < \alpha$ and $P_m\{d(t) < s(t) - \varepsilon|Y_m\} < \beta$.

In contrast to the traditional deterministic approach that assumes a worst-case future scenario, in this multi-stage formulation of RLD, flexibility in future options for corrective actions based on possible updated information is incorporated into the selection of current-stage optimal decisions.

The RLD formulation described above fulfills the basic dispatch function of a cluster. Additional practical considerations may be incorporated as constraints in the formulation. There are two types of constraints: locational and inter-temporal. When the effects of the network, such as line flow limits or power losses, must be considered, locational power balance equations, called power-flow equations, may be added, resulting in vector-valued net supply and net demand. Inter-temporal relations include ramping constraints or energy constraints (e.g., for energy-storage systems) on controllable net supply. The higher the cluster is on the hierarchy, the more constraints may have to be included. For example, network constraints may be necessary in RLD for distribution grid clusters, but may be ignored in building or home clusters. Adding constraints adds complexity to the problem formulation and to the burden of computation. Extending the formulation of RLD to incorporate network constraints is underway [13, 14]. Practical computational methods for stochastic optimization, such as Monte Carlo simulations, scenario-based stochastic programming, or robust optimization, may be fruitfully explored as possible approaches to solving more general RLD problems.

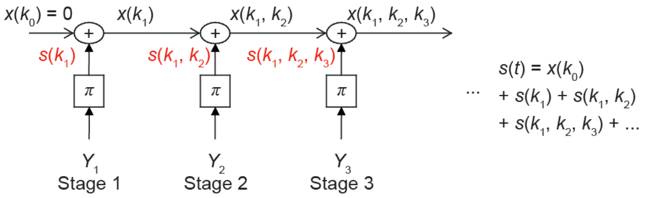


Figure 2. The multi-stage stochastic decision process for the RLD.

4.4 Optimal solution

The optimal dispatch strategy has been derived in Ref. [11] for the RLD formulation presented above for any probability distributions of the net demand. It has a surprisingly simple closed-form solution. The complexity, however, is hidden in terms of the solutions of a set of complex equations. The notation is rather involved for the general case. For the purpose of illustration, let us simplify the notation by considering a specific case where the electricity market consists of a day-ahead, an hour-ahead, and two ancillary services markets, namely, load following and frequency regulation (Figure 3); hence, $m = 4$. The time duration of each market is denoted by $T_1 = 1$ h, $T_2 = 30$ min, $T_3 = 5$ min, and $T_4 = 10$ s. For this four-stage RLD, in the interval

$$t \in [k_1T_1 + k_2T_2 + k_3T_3 + k_4T_4, k_1T_1 + k_2T_2 + k_3T_3 + (k_4 + 1)T_4]$$

the total dispatched net supply is equal to

$$s(t) = s(k_1) + s(k_1, k_2) + s(k_1, k_2, k_3) + s(k_1, k_2, k_3, k_4)$$

Dispatch decisions at each market include buying (producing) or selling (reducing). Buying in market i is denoted by $s_+(k_1, ..., k_i)$ and selling by $s_-(k_1, ..., k_i)$. The electricity prices (costs) of buying and selling in the market are denoted by $c^+(k_1, ..., k_i)$ and $c^-(k_1, ..., k_i)$, respectively. The objective of the dispatch is to minimize the total expected cost, which is expressed as

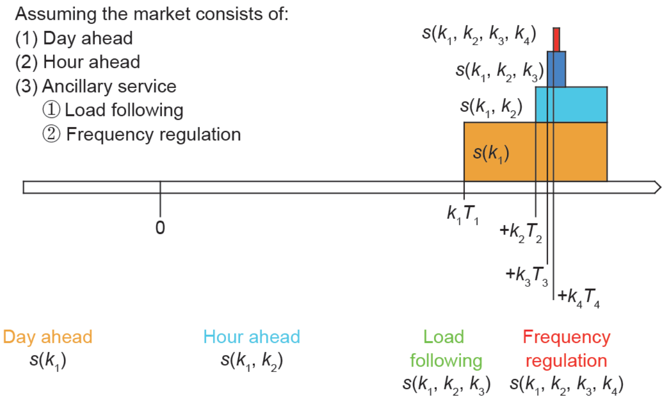


Figure 3. A graphical representation of the accumulated decisions of net supply.

$$\begin{aligned} J(\pi) = E\Bigg\{ & T_1 \sum_{k_1=1}^{24} \left[c^+(k_1) s_+(k_1) + c^-(k_1) s_-(k_1) \right] \\ & + T_2 \sum_{k_1=1}^{24} \sum_{k_2=1}^{2} \left[c^+(k_1, k_2) s_+(k_1, k_2) + c^-(k_1, k_2) s_-(k_1, k_2) \right] \\ & + T_3 \sum_{k_1=1}^{24} \sum_{k_2=1}^{2} \sum_{k_3=1}^{6} \left[c^+(k_1, k_2, k_3) s_+(k_1, k_2, k_3) \right. \\ & \left. + c^-(k_1, k_2, k_3) s_-(k_1, k_2, k_3) \right] \\ & + T_4 \sum_{k_1=1}^{24} \sum_{k_2=1}^{2} \sum_{k_3=1}^{6} \sum_{k_4=1}^{30} \left[c^+(k_1, k_2, k_3, k_4) s_+(k_1, k_2, k_3, k_4) \right. \\ & \left. + c^-(k_1, k_2, k_3, k_4) s_-(k_1, k_2, k_3, k_4) \right] \Bigg\} \end{aligned} \tag{4}$$

The optimal solution is derived using a backward recursive formula, for j starting at 4 and then step by step back to 1. At stage j, the RLD first calculates two thresholds φ_j^+ and φ_j^- as the solutions of the equations:

$$f_j(x) = T_j c^{\pm}(k_1, \ldots, k_j) \tag{5}$$

where $f_j(x)$ is a function whose detail explanation is given in Ref. [11],

$$f_j(x) = -E\left\{ \sum_{k_{j+1}}^{4} \nabla J^*(x, k_1, \ldots, k_{j+1}) \middle| Y_j \right\} \tag{6}$$

Let $x(k_0) = 0$ and $x(k_1, \ldots, k_i) = x(k_1, \ldots, k_{i-1}) + s(k_1, \ldots, k_i)$. At stage j, RLD dispatches according to the simple rule (Figure 4):

$$s(k_1,\ldots,k_j) = \begin{cases} s_-(k_1,\ldots,k_j) = -\left[x(k_1,\ldots,k_{j-1}) - \varphi_j^- \right] \\ \quad \text{if } x(k_1,\ldots,k_{j-1}) > \varphi_j^- \\ 0 \quad \text{if } \varphi_j^+ \leqslant x(k_1,\ldots,k_{j-1}) \leqslant \varphi_j^- \\ s_+(k_1,\ldots,k_j) = \left[\varphi_j^+ - x(k_1,\ldots,k_{j-1}) \right] \\ \quad \text{if } x(k_1,\ldots,k_{j-1}) \leqslant \varphi_j^+ \end{cases} \tag{7}$$

In deriving the solution, estimates of future uncertainties, that is, the probability distributions $P_i\{d|Y_i\}$, $i = 1, 2, 3, 4$, are incorporated into the RLD formulation based on the information that is available one day ahead. The solution gives $(\varphi_1^+, \varphi_1^-)$ and the optimal dispatch, $s(k_1)$, for the day-ahead market. A three-stage RLD with updated (one hour ahead) probability distributions $P_i\{d|Y_i\}$, $i = 2, 3, 4$, will be used to derive the optimal dispatch decision, $s(k_2)$, for the hour-ahead market, and so on.

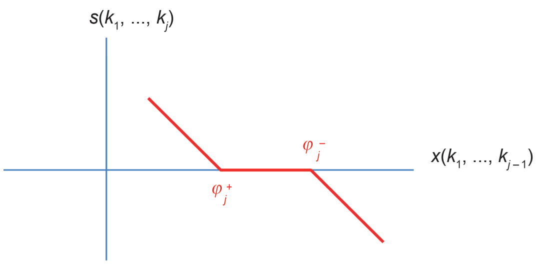


Figure 4. The optimal solution for the example.

5 Electric spring-embedded smart load

Deviations from the scheduled net power balance within the time-step of the scheduling period that are due to fluctuations either in generation or load in a cluster must be smoothed out. In this context, power includes both the real (or active) and the reactive powers in an AC system. The real power is the average power that is generated or consumed. The reactive power is associated with voltage: Sufficient reactive power is necessary to maintain a desired voltage level. In the conventional power system, where the responsibility of ensuring an instantaneous power balance lies in the generators connected to the transmission grid, this function is carried out by the local feedback control of speed governors (for real power) and excitation systems (for reactive power) in synchronous generators. Together, they adjust the output of the generation to follow fluctuating load demand. For clusters on the periphery—distribution grids, micro-grids, and smart buildings and homes—there is no synchronous generator to do the job. We propose instead to work with the loads that are ubiquitous on the periphery in order to smooth out fluctuations.

5.1 Smart load

Some loads are critical in the sense that the proper functioning of the devices or appliances constituting the load relies critically on the levels of the supplied power and voltage to be within very tight bounds. Other loads are not critical to terminal conditions. Resistive loads are in general less critical. Examples of non-critical loads include: ① water heaters, large-scale ice-thermal storage systems, some non-essential lighting, and air-conditioning, in homes and buildings; and ② street lighting on distribution grids or micro-grids. Critical loads are those that end-users care about the most. Such loads include home and office computers, elevators in buildings (when in use), and certain machineries for manufacturing. The operational priority in a cluster is to ensure that the (real) power to and the terminal voltage on the critical load are kept within the tight bounds allowed for its operation. Variations in terminal voltage and real-power input need to be smoothed out.

The idea of a mechanical spring in smoothing out vibrations is well known. A spring is a device that bounces back up after it is pressed down, and that contracts down after it is pulled up. An electric spring (ES) should be a device that pushes the power back up when it becomes low and brings the power down when it becomes high. An ES must perform this task for both real and reactive powers. In terms of reactive power, an ES must have the capability to bring back the voltage when the voltage deviates from the desired value. We have developed several types of power-electronics-based ESs [15–20]. We proposed an "ES-embedded smart load" [15, 16] to smooth out imbalance of generation and load within a cluster, specifically for those on the periphery. So far, three types of ES have been developed:

(1) An ES without a real power source [15, 16];
(2) An ES with a real power source [17, 18];
(3) An ES based on a grid-connected bi-directional AC-DC

power inverter with energy storage [19, 20].

The ES can be connected in series with, or embedded in, a non-critical load to form a "smart load" and the combination is connected in parallel with critical loads, as shown in Figure 5. The smart load behaves adaptively to reduce real power imbalance while maintaining voltage regulation for the critical load [15, 16].

5.2 Smoothing fluctuations

Figure 6 illustrates the way an ES adjusts its (real and/or reactive) power consumption to support the total power input (i.e., supplied) to the critical load. In normal operation, without the ES, as shown in Figure 6(a), the input power p_{in} to the non-critical load p_{NC} and the critical load p_{C} is

$$p_{\text{in}} = p_{\text{NC}} + p_{\text{C}} \tag{8}$$

Assume that p_{C} is considered acceptable to the critical load. Suppose that the input power fluctuates to a different value $p'_{\text{in}} = p'_{\text{NC}} + p'_{\text{C}}$, $p'_{\text{in}} < p_{\text{in}}$, $p'_{\text{C}} < p_{\text{C}}$, and p'_{C} becomes too low and unacceptable to the critical load. In the ES-embedded smart load, as shown in Figure 6(b), however, it is possible to raise the input power to the critical load at the desired value p_{C},

$$p'_{\text{in}} = \left(p_{\text{ES}} + p''_{\text{NC}}\right) + p_{\text{C}} \tag{9}$$

by requiring

$$p_{\text{ES}} = \left(p'_{\text{NC}} - p''_{\text{NC}}\right) - \left(p_{\text{C}} - p'_{\text{C}}\right) \tag{10}$$

The p_{ES} in Eq. (10) is the power consumed by the ES, the power generated (supplied) by the ES is the negative of the consumed, i.e.,

$$p^{\text{G}}_{\text{ES}} = \left(p_{\text{C}} - p'_{\text{C}}\right) - \left(p'_{\text{NC}} - p''_{\text{NC}}\right) \tag{11}$$

The insertion of an ES changes the power consumption in the non-critical load in a manner determined by the characteristics of the critical and non-critical loads. It can be seen that if $p''_{\text{NC}} < p'_{\text{NC}}$, the ES-embedded smart load can "borrow" from the reduction in power consumption ($p'_{\text{NC}} - p''_{\text{NC}}$) of the non-critical load to add to the critical load in order to make up for the shortfall ($p_{\text{C}} - p'_{\text{C}}$). This special feature of the ES that derives power from non-critical loads differentiates it from the conventional approach of using energy storage and voltage control devices for smoothing out fluctuations. The ES acts in the spirit of Robin Hood, that is, to "rob" power from the non-critical load and give it to the critical load. With an ES, non-critical loads, which have greater tolerance to variations, may be adversely affected, whereas critical loads that have higher priority will be stabilized. An example in Section 5.3 below will make this point clearer.

The foregoing analysis is valid for both the real and reactive powers. If the critical load is an impedance load with an impedance $Z_{\text{C}}\angle\theta_{\text{C}}$, then $q_{\text{C}} = |V_{\text{C}}|^2 (\sin\theta_{\text{C}})/Z_{\text{C}}$, where $|V_{\text{C}}|$ is the terminal voltage magnitude at the critical load, and the necessary reactive power to maintain the terminal voltage at the desired value $|V_{\text{C}}|$ is the same q_{C} as before. Eq. (11) for the reactive power applies in this case. For more complex loads, however, the relation between voltage magnitude and reactive power may not even have an analytical expression. However, there is no need for such an expression, as the ES is a feedback-control device that generates the necessary reactive power to maintain the terminal voltage of the critical load. If the necessary reactive power is different from the previous q_{C}—for example, if it is q''_{C} instead—then Eq. (11) should be modified and, as illustrated in Figure 6(c), the required reactive power from the ES becomes

$$q^{\text{G}}_{\text{ES}} = \left(q''_{\text{C}} - q'_{\text{C}}\right) - \left(q'_{\text{NC}} - q''_{\text{NC}}\right) \tag{12}$$

To illustrate the required reactive power from ES, let us consider the case where both the critical and non-critical loads are impedance loads, represented by $Z_{\text{C}}\angle\theta_{\text{C}}$ and $Z_{\text{NC}}\angle\theta_{\text{NC}}$, respectively. Suppose the input fluctuation results in a low voltage without an ES. An ES is added to boost the voltage, as shown in the phasor diagram in Figure 7. The ES generates a voltage $\boldsymbol{V}_{\text{ES}}$ that pushes $\boldsymbol{V}_{\text{C}}$ to achieve a larger magnitude. In Figure 7, the two phasors $\boldsymbol{V}_{\text{ES}}$ and $\boldsymbol{I}_{\text{NC}}$ are perpendicular, indicating that this ES is a passive device, and $p_{\text{ES}} = 0$. The ES is acting in a voltage-supporting (i.e., capacitive) mode. The necessary reactive power generated by the ES is

$$q^{\text{G}}_{\text{ES}} = -\left|\boldsymbol{V}_{\text{ES}}\right|\left|\boldsymbol{I}_{\text{NC}}\right|\sin\left(-90^{\circ}\right) = \left|\boldsymbol{V}_{\text{ES}}\right|\left|\boldsymbol{I}_{\text{NC}}\right| \tag{13}$$

5.3 Example

Figure 8 shows a system consisting of loads connected to a distribution system power supply and a self-generated fluctuating wind turbine. Figure 9, taken from Ref. [16], shows the test results for this system. It can be seen that, with the insertion of an ES, the voltage and the input power to the critical load are stabilized to constant levels, at the expense of somewhat larger variations of voltage and power consumption of the non-critical load.

5.4 Applications

The ES that we have developed is a device that can easily be

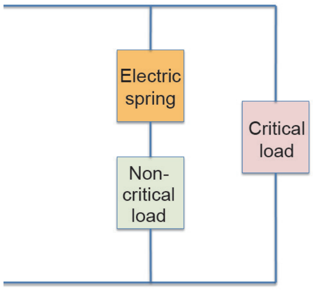
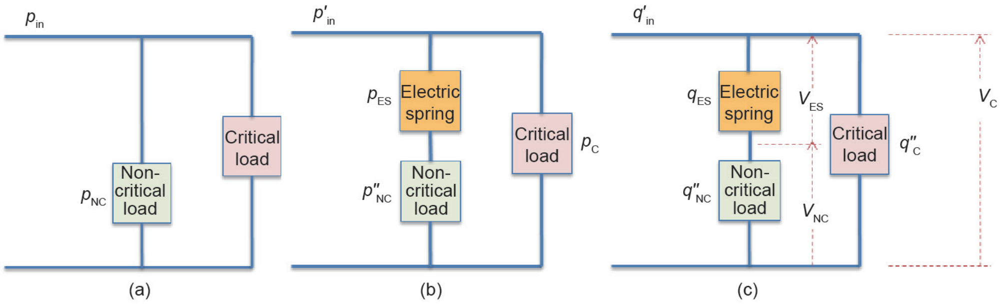


Figure 5. ES-embedded smart load.



(a) (b) (c)

Figure 6. (a) Without an ES in normal operation; (b) with the ES smoothing out fluctuations on critical load; (c) for reactive power/voltage.

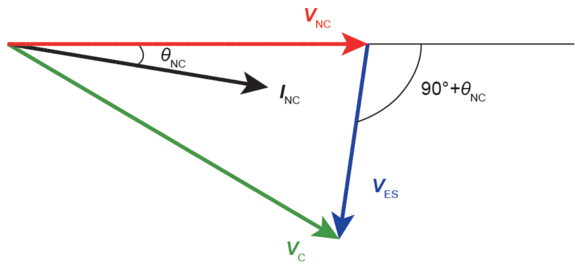


Figure 7. Phasor diagram showing relationship between voltages across non-critical load, critical load, and ES.

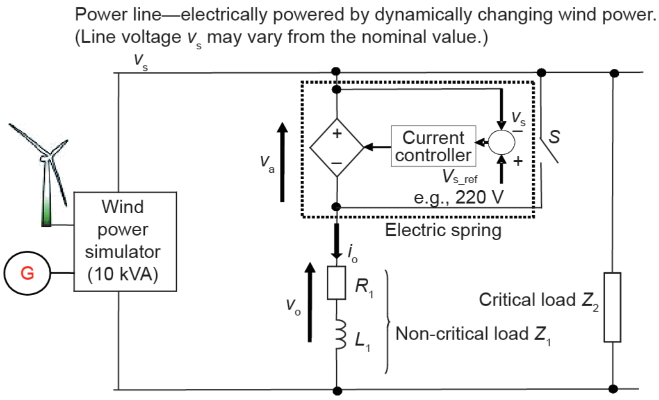


Figure 8. A system for a test case.

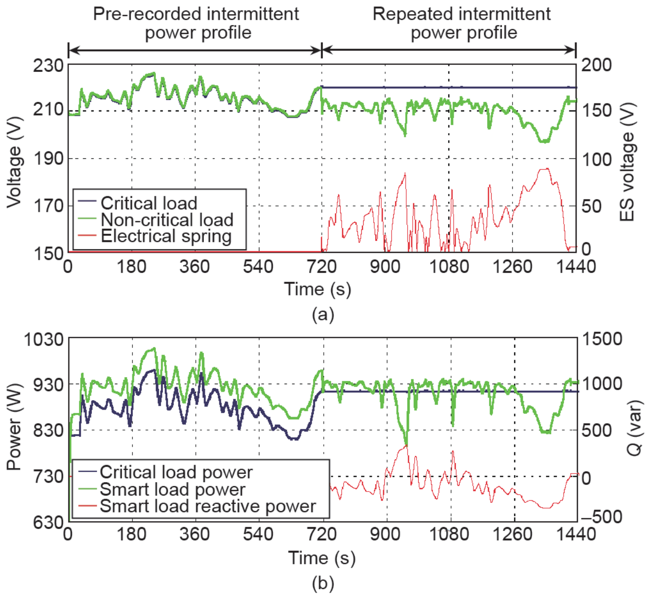


Figure 9. Testing results for the system shown in Figure 8. (a) Voltage; (b) power [16].

individually embedded in a water heater, an air-conditioner, a home appliance, or street lights. We envision that a large number of ESs, spread out over distribution grids that include homes, buildings, and micro-girds, will act like the many mechanical springs in a mattress. Collectively, these ESs will be an effective means to smooth out fluctuations caused by intermittent and variable renewable energy sources, as well as by various forms of unpredictable demand-side and EV management schemes.

If the reduction of power consumption in the non-critical load (Eq. (11)) is not enough to generate the necessary power $p^{\mathrm{G}}_{\mathrm{ES}}$ to damp out fluctuations, an energy-storage device, such as a battery, may be added to the ES for that purpose. In such a case, the ES would use both the power from the battery and the reduction in power consumption of the non-critical load to maintain the constant power supply to the critical load [17, 18]. Obviously, a battery of smaller capacity would accomplish the job in this case than if only a battery is used. A higher proportion of non-critical loads increases the effectiveness of an ES. If the proportion of non-critical loads in a power grid is substantial, an ES could effectively utilize non-critical loads to drastically reduce the imbalance between power supply and demand. A study has shown that the ES-embedded smart load enables the requirement for the storage capacity in a grid for instantaneous power balance to be substantially reduced [21].

For an ES with a real power source, a back-to-back converter has been incorporated into the ES to replace the battery. This scheme eliminates the need for a battery and also expands the control range of the real and reactive powers. A three-phase ES has been introduced into large-scale thermal loads in tall buildings, not only for shaving peak loads and reducing power imbalances between supply and demand, but also for reducing the power imbalance within the buildings [22]. This development has led to new research into adaptive building energy modeling [23]. The incorporation of the concept of the ES into existing grid-connected bi-directional AC-DC power inverters, which exist in many distributed PV systems with energy storage, marks a new development in ES research. Unlike the traditional approach of injecting intermittent real power into the power grid at unity power factor (which is a factor that may cause instability problems), PV systems with slight modifications in the control loops to incorporate the concept of an ES can provide real and reactive power compensation for mitigating voltage and frequency fluctuations in the power grid [20].

From the point of view of a supplier (e.g., a distribution-grid cluster), a large-capacity ES could be used to split the supply mains into two possible connections for consumers: a "regulated mains" providing premium electricity and an "adaptive mains" providing possibly polluted electricity (e.g., a wider range of voltage fluctuation). Those consumers that are connected to the regulated mains constitute the critical load in our configuration and those connected to the adaptive mains constitute the non-critical loads. This arrangement represents a breakthrough in overcoming the technical hurdle that has prevented economists from realizing the idea of "product differentiation" by quality in the electricity business and from allowing price differentiation to consumers according to their needs.

6 Mitigating failures

A cluster must have a mitigating strategy for emergency situation when a sudden and unexpected event, such as a severe disturbance or failure, disrupts the ability of the cluster to maintain the scheduled net power balance. Such an event may have very small probability, but when it happens, the cluster must have the intelligence to detect the presence of imminent danger and have mitigating measures in place to ensure that the imbalance will not propagate and adversely affect other clusters and the rest of the grid. A post-disturbance control must take place immediately to restore the power lost.

At the present time, a sudden and large drop in system frequency in the core cluster of the transmission grid is used as an indicator of a severe power imbalance. A device called an under-frequency relay will be triggered to initiate load shedding, the amount of which is pre-determined according to the load-frequency characteristics of the grid. It has recently been recognized that there is a need for more sophisticated approaches to mitigate system failures in the transmission system in order to prevent cascading blackouts; and an active research effort, referred to as power system resiliency, is underway [24]. A resilient power system is able to anticipate, absorb, adapt, and restore from disruptions. The traditional approach of developing system restoration strategies after a blackout [25], long considered in terms of "thinking of the unthinkable," has recently been evolved into an effort to make the grid self-healing [26].

Mitigating failures in periphery clusters involve three steps.

(1) **Failure detection**: Detecting that the cluster is moving into an emergency state and that it will be unable to maintain the scheduled net power balance.

(2) **Mitigating actions**: Determining the amount and locations of generation or of load (whichever is needed) to cut in order for the cluster to survive the disruption without adversely affecting the rest of the system. Carrying out the necessary actions.

(3) **Restoration strategy**: Developing efficient restoration strategies after severe disruptions causing power interruptions; in other words, minimizing the impact of failures. The risk has two dimensions: probability and impact of failures. The lesser the disruption to power loss is after a failure, the lower the risk of failure is. Efficient restoration essentially reduces the risk.

For clusters on the periphery, a means for failure detection, algorithms for generation/load shedding actions, and strategies for restoring the failure need to be developed, using the intelligence available in the smart grid. This is a research area that is in the early stages of development, even for the core transmission grid. The importance of this topic to the periphery must be recognized, and research must be initiated; however, its development, which depends very much on the details of available technologies and systems, can afford to wait.

7 Conclusions

The future grid must fulfill the vision of the Energy Internet in which millions of people produce their own energy from renewables in their homes, offices, and factories and share it with each other. Electric vehicles and local storage will be widely deployed. Internet technology will be utilized to transform the power grid into an energy-sharing inter-grid. An architecture for the Energy Internet, called GRIP, is proposed. The building blocks of GRIP are called clusters, and include an EMS-controlled transmission grid in the core and distribution grids, micro-grids, and smart buildings and homes on the periphery and are hierarchically structured. The layered architecture of GRIP allows a seamless transition from the present to the future and plug-and-play interoperability. The level of sophistication employed in carrying out the functions of a cluster may vary for different clusters. The basic functions of a cluster consist of ① dispatch, ② smoothing, and ③ mitigation. A risk-limiting methodology is presented in this paper, and a new device, the ES, is developed for smoothing out fluctuations in periphery clusters.

Consistent with the collaborative behavior in the future Energy Internet, the GRIP architecture requires all clusters to schedule in advance their own net power balance and commit to it afterwards, taking into account external power exchange with other clusters. Together, clusters share the operational responsibility of maintaining the instantaneous power balance of the grid. Periphery clusters are therefore empowered to plan (schedule) ahead for their own resources and dispatch (control) them in real time. This is a departure from the present paradigm of passive usage and/or production of electricity where end-users have no responsibility to the system. This proposal of shared responsibility may be the greatest challenge to the acceptance of GRIP. However, we believe that limiting environmental pollution to the community and greenhouse gas emission to the planet are universal concerns and that all citizens must endeavor to prevent the damage to our community and to the planet. In the collaborative era of the Energy Internet, collective efforts will lead to more widespread benefits. The proposed empowerment of the periphery in GRIP architecture allows the most efficient utilization of renewables. Accepting this shared responsibility for sustainable development is a noble cause for all end-users of electricity to undertake.

Energy Internet is a term that has been used loosely by many people with various implications to its technical contents. Recently some people have extended the scope of the Energy Internet from electricity to heat, gas, and other forms of energy in what may be called a multi-energy delivery system [27, 28]. Innovations in integrated energy management are expected to further improve the overall efficiency of energy utilization. The basic ideas in GRIP—object abstraction, encapsulation, collaboration, and distributed and shared responsibility—can be extended to systems with multiple forms of energies. The basic functions of a cluster, however, need to be expanded in order to manage the integrated operation of multiple forms of energies. The GRIP architecture proposed in this paper serves as a good starting point for extending the Energy Internet.

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Compliance with ethics guidelines

Felix F. Wu, Pravin P. Varaiya, and Ron S. Y. Hui declare that they have no conflict of interest or financial conflicts to disclose.

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