GRIP – Grids with Intelligent Periphery: Control Architectures for Grid2050$^{\pi}$

D. Bakken, A. Bose, K. M. Chandy, P. P. Khargonekar, A. Kuh, S. Low
A. von Meier, K. Poolla, P. P. Varaiya*, F. Wu
*Corresponding Author. Electrical Engineering & Computer Sciences,
Univ of California, Berkeley, varaiya@eecs.berkeley.edu

***Abstract*—A distributed control and coordination architecture for integrating inherently variable and uncertain generation is presented. The key idea is to distribute the intelligence into the periphery of the grid. This will allow coordination of generation, storage, and adjustable demand on the distribution side of the system and thus reduce the need to build new transmission facilities to accommodate large amounts of renewable generation.**

***Index Terms*—Distributed generation, renewable integration, control architecture.**

I. INTRODUCTION

Climate change is widely believed to be one of the most pressing problems facing humanity. As a result, there is great interest in the deployment of renewable sources of electricity to reduce carbon emissions from the use of fossil fuels [coal, oil, natural gas] for electricity production. The inherent variability and unpredictability of wind and solar power production poses a major challenge to the integration of these sources into the electric grid operations. The principal purpose of this paper is to offer a control architecture vision for operating Grid2050, the electric grid of year 2050, with large amounts of wind and solar electricity. The essential distinguishing feature of our architecture is the notion of *intelligent periphery*.

We begin by describing the key driving trends that shape Grid2050. This is followed a description of our proposed control architecture. Next, we connect our architectural concepts with similar ideas, concepts, and proposals under development. We present a preliminary set of performance metrics to evaluate competing architectures. We end with a discussion of a possible transition path from the current grid operations to the proposed future architecture.

II. DRIVING TRENDS

Evolution of the electric grid in the coming decades will be shaped by a number of interacting forces. We briefly discuss these below and draw some conclusions on the likely outcomes. We recognize that predictions of the future are subject to many sources of error. Still, there is value in sketching likely future scenarios in designing and judging engineering solutions. In case of energy systems, change takes years and decades. The selection of a system architecture is particularly important since it simultaneously limits future evolution and enables innovations that cannot be foreseen today.

A. Rising Demand

Demand for electricity has increased in the past decades with economic growth, industrial development, and population growth playing critical roles. This growth will continue although factors such as greater role for the service sector, energy efficiency technologies, and moderation in population growth are likely to reduce the rate of growth of electricity consumption in the US. Estimates from the Energy Information Administration suggest that electricity consumption in the US will grow 30% by 2035 [7], while the worldwide electricity consumption is expected to grow by 87% by 2035 [8], driven by rapid urbanization and industrialization in the developing nations. Large-scale adoption of electric vehicles [EVs] will further increase total demand, affecting its temporal and spatial distribution.

B. Fossil Fuel Generation

Currently, fossil fuels [coal, oil, and natural gas] and nuclear power are the primary sources of electricity production. A US utility industry survey [2] notes that 25-35% of traditional generation and transmission [GT] assets are nearing the end of their useful life and another 8% are beyond their useful life. Together with new facilities to accommodate growth, at least 50% of GT assets in 2030 will be new. The new generation assets are unlikely to be based on fossil fuels, because of regulatory policy responses to the threat of climate change,

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D. Bakken and A. Bose are with Washington State University, K. Mani Chandy and S. Low are with Caltech, P. Khargonekar is with the Univ. of Florida, A. Kuh is with the Univ of Hawaii, A. von Meier is with the CIEE and Sonoma State Univ, K. Poolla, P. Varaiya, and F. Wu are with the Univ. of California, Berkeley.

although advances in clean coal and carbon sequestration technologies may affect this prediction. While nuclear generation is favored by many utilities, concern about safety and disposal of spent fuel is likely to limit its growth. In sum, the regulatory uncertainty regarding CO_2 [cap and trade] and nuclear power suggests a future with 40-50% renewable electricity production by 2030-40.

C. Renewable Electricity Production

The movement towards a grid with half its energy from wind and solar power is driven by legislation in many states that sets aggressive renewable portfolio standards [RPS] targets. For instance, California is committed to 33% renewable energy by 2020.

Investment in renewables today receives a 30%-50% subsidy. This subsidy is not sustainable in the long-term and must disappear by the time renewables account for 40-50% of energy production. Thus, a renewable-rich future is predicated on technologies that dramatically lower cost of renewable electric power. Although future renewable deployments will use a mix of promising options, we focus attention on two extremes, which we call concentrated and dispersed deployments. The contrast between them will illuminate our choice of control architecture.

A concentrated deployment uses large grid-scale generation plant [wind farms, concentrating solar thermal plants and large PV farms] at locations with exceptionally favorable wind and solar power and connected to the core transmission grid. New transmission facilities will be needed to bring large-scale renewable power to the bulk power grid [9], [14], [15].

A dispersed deployment uses small-scale PV and wind generators connected to the distribution system. Here we include both wholesale and retail distributed generation. In principle, distributing dispersed renewable power would create a much lower need for additional transmission facilities.

Concentrated deployment adds to the [bulk power] core of the grid; dispersed deployment enriches the periphery of the grid.

D. New Technologies

Three new technologies are essential to integrate renewable generation into the grid.

Energy storage is essential to overcome variability and uncertainty. Projections suggest that battery costs are likely to rapidly diminish in view of large research and development investments in a variety of battery technologies. There are also large-scale experimental/commercial projects involving compressed air, flywheels, etc. Energy storage is a potential alternative to fast-acting fossil-fuel based spinning reserve.

Large-scale sensing and communications will be needed both to improve prediction of wind and solar power and to monitor demand [1]; the latter is aided by the deployment of advanced metering infrastructure. Phasor measurement units [PMUs] will improve control and management of the power grid through better state estimation.

Demand response is another alternative that can reduce peak power constraints imposed on generation and transmission facilities. In concentrated deployments, demand response takes the form of reductions in large industrial/commercial loads. In dispersed deployments, it can take the form of deferred energy consumption in EV charging and domestic appliances.

E. Operational Challenges: Centralized vs. Distributed control

The operational challenge posed by renewables is to design a communications and control architecture that reliably, effectively and economically accommodates the variability and uncertainty of renewable power.

A concentrated deployment requires the centralized control architecture used today by Independent System Operators [ISOs]. In this arrangement, ISO purchases generation and reserves at various time-scales [24-hour, 1-hour, 15-min, 5-min ahead] to meet changes in demand. ISO treats variable generation [VG] from renewables as negative load, and thus VG adds to uncertainty in load. This increased uncertainty adds complexity and cost to unit commitment, security-constrained economic dispatch, real-time power balancing, and automatic generation control. In particular, there is a corresponding increase in the required purchase of operating reserves. One recent study [3], for example, estimates that accommodating 33% renewables in CA by 2020 will require 3,000-5,000 MW of regulation reserves for balancing and ramping services from fast resources [hydroelectric generators and combustion turbines] during morning and evening ramp hours. For an international comparison of operating reserves provisioning for wind power integration, see [18].

A dispersed deployment suggests a distributed architecture in which control intelligence is distributed to the periphery that tightly coordinates geographically collocated renewables, storage, and deferrable demand. Since energy flows at the periphery will be much more dense than under centralized control, there will be less need for additional bulk power transmission and less need for additional reserves. The intelligent periphery will be able to strengthen the core [in terms of stability and resilience] at lower cost.

III. INTELLIGENT PERIPHERY OF GRID2050

The most important distinction between the centralized control of the grid, the current paradigm, and our vision of the intelligent periphery can be articulated as follows.

Under centralized control, all decisions that affect overall system efficiency, stability and security are taken by the ISO, with the participation of large generators and load-serving entities. The ISO's view of the system extends out to substations; it is essentially blind to what happens in the periphery, 'under' the substation. It does not know how many EVs are charging or when; how much power is being generated by distributed renewables or when; or how much of residential or small-scale industrial load is deferrable.

Not knowing what is happening in the periphery and unable to affect demand, storage, and supply decisions in the periphery, ISO merely aggregates these as a variable net load at the transmission substation. The resulting requirement to counter this aggregated uncertainty in the worst case results in expensive and inefficient operations by the ISO [and bulk power providers]. The ISO must over-provision the grid: it must have much larger transmission and reserve capacity. The ISO also cannot take advantage of the economies from tight coordination of distributed resources.

By geographically distributing all small-scale decisions of supply and demand [below the substation], the intelligent periphery [IP] will encourage and incentivize the extraction of economies and efficiencies that are hidden from centralized control. It is illuminating to draw an analogy. The telephone network is centralized: the demand for a voice call is centrally managed by a sophisticated Signaling System 7 [SS7], which first sets up an end-to-end 64kbps dedicated circuit between two dumb telephones. The internet, by contrast, has a relatively dumb high-speed core that merely routes packets whose pace is controlled by intelligent terminals. Surely, there are major differences between this telephone vs. internet analogy and the centralized core grid control vs. intelligent periphery situation. What will be common, we believe, are the roles of distributed intelligence in unleashing unforeseen innovations.

IV. GRIP - ARCHITECTURE FOR GRID2050

Our working definition for architecture is the *system level structure* of the interactions between sensing, communication, information processing, control decisions, and actuation working in concert to manage and control the electric grid. We are mostly concerned with information architecture. With suitable choices of hardware components, algorithms, and software implementation, this information architecture becomes a *distributed cyber-system* which interacts with the *physical energy system* - generation, transmission, distribution, and consumption leading to the *cyber-physical electric energy system*. We propose the following qualitative goals for evaluation of competing architectures. We will define some quantitative metrics subsequently.

A key feature of the proposed architecture is that it equips the *GRid with an Intelligent Periphery*. Therefore, we have labeled it the *GRIP architecture*.

Key Goals for the GRIP Architecture

(a) Reliability: The current electric grid has been engineered to achieve a very high level of reliability. Any future architecture should ensure at least this level of reliability if not increase it. See [19] for a discussion of grid reliability issues in the context of smart grid integration.

(b) Differentiated power quality: In the current electric grid, all customers get the same power quality. However, due to significant increase in variability, it may be more efficient and economical to allow for differentiated power quality. Price sensitive demand, deferrable loads, and other demand response technologies are recent examples. It should be noted that differentiated quality does not mean lower quality or reliability. It simply is the idea that (certain groups of) customers may engage in price/quality trade-off.

(c) Enable community choice: It is desirable for local communities to make choices for electricity generation and consumption in accordance with their lifestyle, environmental, and economic preferences. Such communities may, for example, use their extra generation to profit in the electricity market.

(d) Enable innovation: System architecture should be such that innovations in generation, consumption, storage, and information technologies can be readily incorporated through suitable economic and societal structures. It is particularly important to realize that innovations are unpredictable and therefore architecture should be maximally flexible.

We next describe our vision for Grid2050 architecture. It is depicted pictorially in Figures 1-3. This architecture is framed around certain key concepts as follows.

Clusters are collections of electric grid system resources. Two main cluster types are: A *Resource Cluster* [RC] is a [geographically dispersed, but usually homogenous] collection of resources that supply a service [ex: storage, demand response]. Current examples: community solar farms [5], and commercial refrigeration resources offering demand response that are managed collectively [10]. A *Balanced Cluster* [BC] is a [local, but diverse] col-

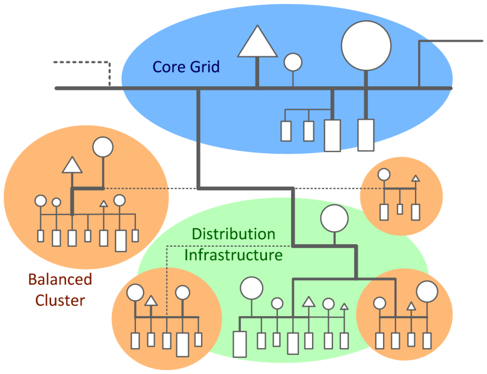

Fig. 1: Layered Architecture

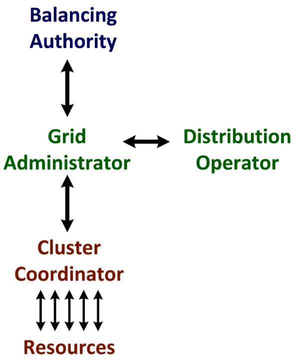

Fig. 2: Data Flow

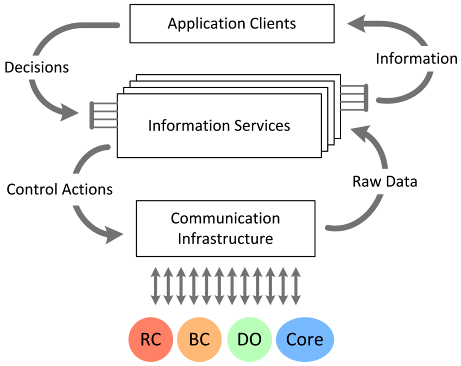

Fig. 3: Distributed Control Loops

lection of resources that largely achieve internal power balance. Any remaining mismatch [designed to be much less uncertain and variable] between power consumption and production is met by contracted imports and exports [over appropriate time scales] from other clusters or the core transmission grid. Balanced clusters aggregate their resources to present reduced and managed variability to the grid. Thus, they mirror on a small scale the function of a larger grid balancing authority. Current examples include zero-net-energy buildings [22], Community Choice Aggregation jurisdictions [17]. BCs relieve the core grid of the need to acquire reserves to counter internal demand and supply variations. Further, a BC may increase overall system resilience if it can be disconnected [islanded] without affecting grid stability.

Cluster Coordinators [CC] manage resource clusters in order to meet a variety of objectives [ex: reduce variability, conservation, increase profit, or promote a green mandate by maximizing renewable generation]. To maintain internal balance, the CC must have sufficient control over each resource and device within the cluster; in reality, the degree of control authority will vary. A major objective for a cluster coordinator is to reduce the variability and uncertainty through coordination of flexible resources and uncertain generation. A key function of the cluster coordinator is to prevent potential conflicts that arise in peer-to-peer interactions.

Grid Administrators [GA] represent clusters in a geographical region to a larger balancing area authority or system operator of the core transmission system. The GA may enter into contracts as a supplier of generation or ancillary services [ex: storage, reserves] to the grid, as a load-serving entity, or as a dispatchable load, by combining the offers of its constituent clusters. The intermediary role of the grid administrator is to present a single point of contact - thus relieving the communications burden - to the ISO responsible for wide-area stability across an extensive geographic region.

The Distribution Operator [DO] services the local distribution infrastructure in the legacy grid. The DO may lease lines, but is not usually an active market participant.

Information Services and Application Clients Resources and devices transmit data about their current state and forecast their future state to CCs, who run Information Services to achieve the cluster's control objectives. This represents a dynamic optimization problem under uncertainty. For an illustration of the dynamic optimization problem see [21]. The resulting information is sent to the GA, who aggregates the forecasts of the individual clusters and executes Application Clients. These applications include resource management as well as infrastructural operations such as network reconfiguration, which the GA undertakes in cooperation with the DO. The layered information architecture provides the information appropriate to the decisions made by CC's and GA's. The transformation from data to commands forms a feedback loop as shown in Figure 3. In a naïve implementation of such a distributed coordination and control scheme, there would be hundreds of thousands of loops. We envision that these loops will employ *common information services* that process the data into a set of sufficient statistics which summarize the state of the peripheral devices. These statistics are used by CC's and GA's to run applications that produce the commands to actuate the resources.

We note that this is simply a framework for distributed control and coordination. Most importantly, we assert that this layered architecture will allow us to realize the key architecture goals described earlier. Its actual realization will require the development of a collection of hardware and software components which will interface with the physical power system and together provide electric energy to the end users. It will also depend on appropriate economic arrangements to reap the benefits and avoid the possible inefficiencies.

V. RELATIONS TO OTHER ARCHITECTURAL CONCEPTS

The Grid2050 architecture discussed in the previous section can be related to a variety of concepts in prior research efforts. In this section, we provide some of these connections. This is not a comprehensive summary of research efforts on control and coordination of distributed electric energy resources. We have focused narrowly on key architectural concepts. We expect that such connections will enrich future research efforts and our collective understanding of the key issues and possible solutions.

A. *Microgrid*

Microgrid is a very well known concept [4] for coordinated management of distributed generation, storage, flexible demand, etc. Since a microgrid is designed to operate in an islanded mode as well as grid connected mode, it is a form of balanced cluster. On the other hand, a microgrid does not participate [or is not specifically designed to participate] in the electricity markets.

B. *Virtual Power Plant*

The key idea of a virtual power plant [VPP] is a *managed collection* of distributed resources [microgeneration, flexible demand, storage] which appears as a traditional generator to the core transmission grid. A VPP can then act like a familiar element in the various grid operations. For example, a VPP can participate in the wholesale electricity markets as a single entity. It can also provide reactive power control for voltage support to its constituents. The key to a VPP is a suite of algorithms implemented in a software package that interfaces with the physically distributed resources through various interfaces. The VPP concept has been studied in depth in the European FENIX [Flexible Electricity Network to Integrate the eXpected "energy evolution"] project [12]. A VPP is an example of a balanced cluster and thus fits into our architecture. Currently, Electric Power Research Institute is working on a similar project with American Electric Power.

C. *DISPOWER*

A very large European project entitled "Distributed Generation with High Penetration of Renewable Energy Sources" [DISPOWER] [6] investigated a variety of power systems issues that are related to the Grid2050 architecture in our paper. It is difficult to directly map elements of DISPOWER research results at the architecture level discussed in our paper. Nevertheless, we expect that ideas from DISPOWER projects will be beneficial in the detailed development of the Grid2050 distributed control system.

D. *NIST Smart Grid Framework*

US based National Institute for Standards and Technology (NIST) has produced a framework and road-map for the smart grid interoperability standards [20]. As part of this framework, NIST has also developed a "Conceptual Reference Diagram for Smart Grid Information Networks" [[20], pp. 35]. This is a rather comprehensive diagram that covers the large variety of entities that will be in any future evolution of the grid. These efforts are aimed mainly at the key communications and networking aspects of the smart grid. Clearly, such standardization and interoperabilty standards will *enable the implementation* of our Grid2050 distributed control and management architecture. On the other hand, as we develop a detailed technical understanding of Grid2050 architecture, it should influence the future development of the communications and networking infrastructure.

E. *Multi-Agent Systems*

There are many research efforts that utilize multi-agent systems [MAS] framework for distributed control for a variety of power systems problems [13], [16], [23]. There is no direct mapping between our architecture and multi-agent systems based approaches. However, cluster managers and grid coordinators [and applications] could be implemented using MAS technologies.

VI. PERFORMANCE METRICS

How will we measure the performance of this architecture? Indeed, this question can be posed more broadly: how can competing architectures for Grid2050 be compared? As we mentioned in the previous section, there are alternative architectures and approaches that are generally aimed at similar goals as this paper. These research efforts have different goals and address different parts of the overall problem. Hence a direct comparison is not possible.

In developing performance metrics, we have focused on certain critical power systems engineering and economics variables that will be impacted by the choice of architecture. Perhaps, the most important metric is the amount of renewable generation facilitated. This metric depends on a variety of factors beyond control and communications architecture such as social policy, public opinion, and costs. We next list a [partial] set of metrics that are more closely linked to architectural choices that should be considered in future comparative evaluations.

(a) Operational reserves: Uncertainty and variability are the key distinguishing features of renewable electricity sources. Therefore, additional operational reserves are needed to ensure the required level of reliability. Distributed control architecture will have a significant impact on the needed operational reserves.

In view of the high costs of reserves and the negative carbon impacts, *extra operational reserves* needed for achieving a given level of renewable generation penetration is an important performance metric.

(b) Total distance weighted energy flow: $\sum E_i L_i$ where the sum is taken over all power lines in the grid, E_i is the energy flow and L_i is the length of power line i. This quantity is also related to power losses.

(c) Local self sufficiency: For each balanced cluster j let T_j be the average of absolute values of energy imports and exports over a suitable time period and C_j be the total energy consumption by members of the cluster. Define the self sufficiency metric: $S_j = T_j/C_j$. System level metrics that combine S_j across all balanced clusters in the grid, e.g., average of S_j or maximum of S_j over all j would indicate how efficient the architecture is in ensuring local balancing of consumption and generation and minimizing the burden on the core transmission system.

In addition to the quantifiable metrics, we add several very important objectives which are not easy to measure.

(a) *Innovation enabled:* This quantity is hard to measure *a priori* but can be judged on the basis of previous technological developments such as the internet and highways.

(b) *Resilience:* This quantity can be evaluated using simulations of fault scenarios.

(c) *Security:* This is mostly determined by the communications protocols and various IT policies.

VII. TRANSITION PATHS

A key advantage of the GRIP architecture is that it is backward compatible and innovations can be integrated on an incremental basis and at various levels. The examples of microgrid, smart buildings, and VPP, illustrate such incremental deployments. By providing a clean interface to the grid, GRIP provides a framework for a more systematic development of similar innovations below the transmission substation.

One can imagine various hardware- and software-centric enterprises that would find profitable niches in the Intelligent Periphery. For example, communications providers can supply IPv6-addressable sockets that can turn on or off [dumb] devices through commands sent over PLC [power-line carrier]. A circuit designer can develop a small remotely programmable switch that can channel power to an appliance like and EV from a PV or from the distribution system. A consumer-survey company can create a database of the distributed resources for a potential cluster, and estimate the potential savings from tight coordination. Social networking software can encourage people in a potential cluster to participate in order to reduce their carbon footprint. All such efforts are facilitated by and in turn promote, the Intelligent Periphery.

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