Towards Enhanced Power Grid Management via More Dynamic and Flexible Edge Communicaitons

This is an extended version, with active hyperlinks (which IEEE does not allow) of the following paper:

D. Bakken, A. Askerman, A. Srivastava, P. Panciatici, M. Seewald, F. Columbus, and S. Jiang. "Towards Enhanced Power Grid Management via More Dynamic and Flexible Edge Communications", in Proceedings of the Fog World Congress, IEEE and OpenFog Consortium, Santa Clara, CA, Oct. 30, 2017. This paper is available at GridICT.net

David Bakken, Alex Askerman, Anurag Srivastava
School EECS
Washington State University
Pullman, WA, USA{bakken,alex.askerman,anurag.k.srivastava}@wsu.edu

Patrick Panciatici
Power Systems Expertise Department
RTE France
Versailles, France
patrick.panciatici@rte-france.com

Maik Seewald
Chief Technology & Archhitecture Office
Cisco Systems
Munich, Germany
maseewal@cisco.com

Frank Columbus, Song Jiang
Utilities Solution Management
Cisco Systems
San Jose, CA
{fcolumbu,seanjian}@cisco.com

***Abstract*—In the last few years cloud computing has become of great interest to the electricity sector. Edge computing (and its close cousin, Fog computing) is a complement to cloud computing: it exploits devices at the logical ends of networks. This paper outlines the potential for edge computing to help power grids. It overviews power grids and the "smart grid", including how grids are getting increasingly stressed. It then explains the limitations of information and communications technology (ICT) in today's grids and how much better ICT can help them. The Fog Pillars are then analyzed in how they can help power grids. Finally, This paper explains candidate algorithms for edge computing, broken down by ICT platform services, power services, and power applications.**

Keywords*—*Edge computing, fog computing, cloud computing, power systems.

Contents

I. Introduction 2
A. Power Grids Today 2
B. The Emerging Smart Grid 2
C. Power Grids are Increasingly Stressed 3
D. ICT Limitations Holding Back the Smart Grid 3
II. opportunities for Smart Grid ICT 5
A. More Data Sharing and Better Communications 6
B. Robust Coordination 6
C. Cloud Computing 7
D. Edge Applications and Services with Fog 7
III. Fog Pillars for Electric Grids 7
IV. Candidate Algorithms for Edge Services 8
A. ICT Platform Services 8
B. Power Services 8
C. Power Applications 9
V. Testbed 10
VI. Conclusions and Future Work 11

I. INTRODUCTION

A. *Power Grids Today*

The electric power infrastructure in the USA has evolved over the last century from small, independent, community-based systems into what it is today. The state of the system (voltage phasors at all power busses) is continually estimated, and, with this, control decisions are made. Electricity markets are intimately tied into its operation; indeed, it could be said that power grids today are foremost driven by economics, while trying to maintain reliability constraints.

As a result, electric power grids such as the Eastern grid in North America and in Western Europe are the most complex machines built by humanity. Indeed, the US National Academies judged electrification as the biggest technical achievement of the Twentieth Century, ahead of such technologies as computers, space travel, automobiles, and airplanes. Power grids must keep supply and demand in balance in real-time over great distances. Historically, a vertically-integrated utility managed all of these 3 fundamental roles — generation, transmission, and distribution — in its service territory.

It is frequently said that, were he to come alive today, Edison would still recognize and understand today's power grids [1]. AC generators send current over long distance transmission lines (usually) and then it fans out to customers in a radial fashion in distribution systems. Very little of this has changed fundamentally in the last century in terms of the physics and the basic devices.

The Information and Communications Technology (ICT) infrastructure is largely based in 1970s technology, put in place after a large blackout in New York and augmented since then in a piecemeal fashion with Layer 2 technologies and IP, generally with no knowledge of best practices in other industries. Before the 1970s, a utility control center had no way of sensing anything in its territory outside of the control center. Today, they still have far less data sharing that would demonstrably be beneficial, due to a myriad of market, regulatory, legal, and other reasons.

B. *The Emerging Smart Grid*

Today's power grids have been changing rapidly in recent years. Most grids were deregulated about two decades ago: the vertically oriented utilities retained transmission and distribution, but generation was made competitive to allow competition from new generating companies. This deregulation made life more complicated for utilities, but Edison would still recognize them.

In the last decade there have been many new renewable energy sources (RES) deployed, mainly solar and wind. Governments everywhere are mandating large percentages of renewables. For example, Germany mandates 35% by 2020, 50% by 2030, and 80% by 2050.

This massive integration of generating units based on RES with nearly zero marginal costs and mostly connected through power electronics to the grid imposes us to rethink how to protect, control and optimize power systems. Moreover, the low controllability of RES generating power invites solutions based on storage devices and demand responses to balance the system.

All classical textbooks explain that it is not possible to store electricity (at a large scale), that demand is not sensitive to price, that large synchronous generators are imposing the power system dynamics and that marginal cost is a fair and efficient index to price electricity.

C. *Power Grids are Increasingly Stressed*

The recent evolutions are really disruptive: historical design assumptions for power grids are rapidly becoming obsolete. Edison and even Tesla would decreasingly be able to understand what is going on. Indeed, Resnick Institute of Caltech begins a report with a bold statement [2]:

> *The transformation occurring across the world's electrical systems represents one of the greatest technological challenges industrialized societies have undertaken. Reconfiguring a grid designed to carry power one way from reliable generation sources managed by few agents to a system increasingly laden with unreliable wind and solar energy while involving millions more participants using advanced technologies will introduce a high degree of uncertainty and variability into the future grid. These changes potentially threaten reliability of electrical supply and must be carefully choreographed to avoid widespread perturbations in cost, reliability and efficiency.*

There is widespread agreement among power researchers that grids are getting increasingly stressed, and thus likely less stable. There are a number of factors involved. First, growth of long-distance capacity is way behind what should be built based on projections for load growth; more "miles times megawatts" is inherently destabilizing. Almost all large blackouts in recent decades are focused around imbalances between the ends of long-distance transmission corridors. Second, RES technology does not provide any rotational inertia. A big turbine from a natural gas, coal, or hydro generator is spinning at the grid's frequency and has a huge amount of physical inertia. This can absorb a lot of energy if there is a fault in the power grid. Renewables do not provide any physical inertia: they are necessarily isolated from the grid by power electronics (they cannot be controlled to rotate at the grid's AC frequency). Third, the addition of semi-independent microgrids. Fourth, "Prosumers" at the edges of the distribution system that not only consume electricity but also can produce it. Distribution systems were not designed for two-way flow of either electricity or data.

All of the above factors can be greatly mitigated by much better ICGT. There is thus an urgent need to rethink both economics and dynamics of power systems. Indeed, Hung-po Chao, directory of market strategy and analysis at ISO New England, states that

> *Without growth of computational power, the electrical system cannot cope, not even with technology that we installed 10 years ago [3]*

Ad hoc and piecemeal patches to marginally adapt the historical legacy design are probably not a good approach even if the migration path is a critical issue. Though, due to regulatory, technical, and historical reasons, that tends to be the *modus operandi* of power grids virtually everywhere, especially in the ICT fields because they are far from their core competencies.

It is clear that transmission grids are and will remain for a long time critical infrastructures in our low carbon advanced societies where more and more applications need electricity (E.V., heating/cooling) whatever the local conditions.

D. *ICT Limitations Holding Back the Smart Grid*

Some digital solutions have been implemented for power grid protect and control but these solutions just mimic the legacy analog functions without taking all the advantages brought by digitalization. The existing applications for example at the substation level are simplistic, the complexity doesn't go very far beyond something like: "if (condition) then {action}". Modern computers are obviously capable of much wider calculation than this. Their design is generally based on an equipment-by-equipment approach (i.e., on a parwise basis), the functional objective is achieved by an implicit coordination of specific equipment behaviors based on local measurement. Moreover, the settings of this simplistic functions are most of the time, persistent very locally, difficult to update and impossible to adapt dynamically depending on the context.

This was consistent with a rather static environment reasonable in the 1970s, and thus not unreasonable then. Computational power of computers and the performances of telecommunication systems have increased a lot during the last decades now the performance requirements for a large portion of power grid applications can be reached using standard hardware and high level programming languages. Advanced ICT technologies offer great hope for managing the future grid; fog and edge computing can be a be enabling technologies to meet the needs of future power grids.

One big problem in today's power grid ICT systems is that there is no meaningful QoS. Indeed, many utilities have separate fiber links for remote protection schemes (RASs) and allow virtually no traffic on them (very low utilization), because they are afraid of not getting fast responses. A recent survey is a case in point. The North American Synchrophasor Initiative (NASPI) is an initiative involving utilities that are ipso facto leading-edge (for the power grid, anyway) utilities, researchers, and government agencies (DOE, NERC). It recently conducted a survey of its utility/ISO members [4]; this is well worth a read if the reader is interested in the sad state of power grid WANs. Among its findings are:

- Most network links have a wide range of traffic on them.
- There is very little effective redundancy.
- 68% of respondents replied that they have no QoS mechanisms; 16% relied on MPLS-TP (which has too coarse granularity), and 10% relied on the WAN service provider (which has virtually zero hard real-time customers).
- 79% utilize no middleware, despite this being best practices in virtually every other industry for at least 15-20 years [5]. A further 21% rely on application-layer pub/sub or multicasting, i.e., pushing the complexity to the application programmers (who are generally power engineers with one class in C/FORTRAN and one in MATLAB, and who have not heard of the term "distributed computing" before).
- 74% report that WAN management is done in-house (consider the core competencies involved); 16% is by a vendor (consider the small market here).
- 88% report that their service provider does not alert them if the SLA/QoS is violated
- 11 reported that they do not monitor network SLA/QoS (latency and jitter) for their applications, while only 4 reported that they did.
- None of the respondents did anything in real-time (or even a timescale of hours) in response to excessive latency and jitter; most were on the order of weeks or months (working with their network team and stakeholders, contact service provider, etc.).

The above numbers are breathtaking, given the criticality of some of the remote protection schemes that are needed to prevent blackouts (and, if they fail, including not acting fast enough, there WILL be a blackout almost always).

Included in above findings is the fact that power grid ICT infrastructures are not actively managed, at least not without humans and scheduled meetings in the loop (i.e., not at the timescales needed for the grid to respond to some crises).

In other cases, it is power engineers (without the appropriate background) designing power network protocols for sharing data. Some of them try to compensate for no QoS by overkill that is a textbook case of being (arguably) locally optimal and globally disastrous; e.g. resending an important alarm message up to 1000 times [6] to hopefully ensure that it gets delivered.

Many other things are hardcoded in the power grid: network links, backup nodes, naming, parameterization of breakers and other devices (utilities have to send out a technician to a substation to change them), etc. Other things that are hardcoded: network links, backup nodes, naming, parameterization of breakers and other devices (utilities have to send out a technician to a substation to change!).

II. OPPORTUNITIES FOR SMART GRID ICT

Advanced ICT solutions to allow an efficient utilization of the existing grid assets and to cope with variability of power flows without overinvestment in expensive grid assets [7]. Digital solutions can be used to improve different aspects of power grid management but all the functions have not the same criticality. The requirements for the associated ICT systems should be different. We can define three main classes of functions: asset management, protection and control, optimization.

1. Digital solutions can be used to enlarge and to have better knowledge of the power grid capacities. Power grid capacity is the range of operating conditions in which the power system can remain for an infinite time without any problems and with a controllable degradation of assets (feasible domain). Dynamic rating, monitoring, predictive maintenance based on Internet of Things are the key functions which should allow these improvements.

2. Digital solutions enable better protection and control of the power grid. When a contingency hits the system, the operating point can move outside the feasible domain where it is impossible to remain for a long time (less than few seconds). Post fault fast and reliable actions should bring back as soon as possible the operating point inside the feasible domain. Advanced ICT functions for hierarchical protection and control system customized to local conditions: windy, sunny, urban, rural area are certainly key enablers in order to achieve this goal. We need a flexible framework to select perhaps dynamically where and how to implement these versatile and distributed “intelligence”: from substation level to group of substations up to power grid control center. Model predictive control is a possible relevant framework.

3. Distributed control is a promising mean to cope with the increasing complexity of power grid. We understand that it is what nature had done in many cases. For example, if we try to understand why the animal vision is so efficient, we notice that eyes are not sending the full information captured by their local sensors to the brain. In fact the brain configures the eyes to send only the relevant compressed information depending on the context based on a prediction; this is why magicians can fool us!

4. Power system optimization can use advanced ICT solutions to allow and to implement new market mechanisms extracting the maximum value of smart meters, demand response programs, smart buildings/homes and to allow for example peer-to-peer electricity commercial exchanges based on Block Chain technology.

This digital transformation is an enabler and a booster of the energy transition and impacts all processes but digital solutions for critical mission applications must be addressed with care.

A. *More Data Sharing and Better Communications*

It is well understood that much wider data sharing can greatly help power grid stability [8,9]. The lack of widespread sharing (something readily supportable by today's technologies) has consequences [10]. As noted in [11] (and by others):

> *With the exception of the initial power equipment problems in the August 14, 2003 blackout, the ongoing and cascading failures were almost exclusively due to problems in providing the right information to the right place within the right time.*

This failure of delivering sensor and other data was not unique to this US-Canada blackout, in fact it was a major contributor to the 2003 blackout involving the Swiss-Italian border, and other major blackouts. In most of them, serious problems occurred an hour or more before the blackout, but were not acted upon due to inadequate situational awareness of the operators, which was inevitable given the poor data communication infrastructure and insufficient sensors. Ref. [12] concludes with a list of the 4 root causes of major blackouts (especially those in 2003), and **the first root cause given is a lack of reliable real-time data**. For more details on these communication limitations, see [10,13].

The power grid 's most challenging application need lower latency — some on the order of 15-20 milliseconds over hundreds of miles — with high availability [14,15]. No commercial market that meets these extreme needs with the granularity of control and monitoring that is required. [14,16].

However, GridStat has been designed to do just this [14,16,17], as described below. And the Industrial Internet of Things (IIoT) also offers hope, at least to the extent that it is designed for the wide-area and with these extreme requirements in mind [18].

MPLS-TP removes most of the nondeterminism in MPLS, though it has only a coarse granularity — there are only 6 classes of service, not per-sensor-flow QoS— and, unfortunately, there is no guarantee that a higher "class" gets better treatment [19]. And all sensor flows in a given class — which can be a large number of diverse flows — get treated exactly the same. Software Defined Networks (SDN) such as OpenFlow offer the hope of deploying new network protocols without having to disturb existing infrastructures. However, SDN is not a panacea [16].

But even if GridStat, IIoT, MPLS-TP, FlexLSP, and SDN offered all that was needed for power grids, the architecture of the applications and systems is mostly static and client-server. Distributed intelligence via more data sharing and Fog and Cloud technologies is greatly needed to give more flexibility and the ability to push out apps needed for the changing conditions of a grid and allow pieces of distributed intelligence to share data and coordinate peer-to-peer, not having to go through today's fixed client-server relationships (move involving a control center).

B. *Robust Coordination*

As noted below, more and more power algorithms are moving from the limited centralized control center model to being decentralized. These increasingly require distributed coordination [20]. While platforms such as Paxos and Raft are useful, a broader range of distributed consensus algoritms, supporting a wider range of tradeoffs and failure models is needed [21].

DCBlocks was designed just for this purpose [21]. So far we have designed, implemented, and evaluated DCBlocks solutions for RAS for wind curtailment [22,23,24,25], voltage stability control [26], and state estimation [26]; we have identified other use cases including frequency control, optimal power flow, reactive power control, and inverter control [21].

C. *Cloud Computing*

The cloud is an obvious candidate for the power grid, and has garnered great interest from the power sector in recent years [27]. Many power applications of the form of "evaluating a candidate configuration or explanation" are embarrassingly parallel, and there is much possibility here [28]. However, advances need to be made in cloud technology until it is suitable for the power grid [29].

GridCloud is ARPA-E funded technology developed to manage multiple instances of state estimation in the Amazon EC2 cloud for reduced latency [30]. This technology was the core of a pilot project involving ISO New England in 2015-2016 [31], continued by NYPA, and involving WSU's GridStat, Cornell's ISIS^2 and CloudMake, and other technologies.

D. *Edge Applications and Services with Fog*

Edge computing has great potential to help the manageability and stability of power grids. Pushing computations closer to the sources of sensor data and controlled actuators can save a lot of bandwidth, and allow for much quicker responses than possible by a centralized control center. They also enable these computations to utilize much more detailed, localized data than is feasible to send to the control center, for both bandwidth and timeliness reasons. Standard sensor fed clouds cannot meet the needs for fast latency in these bandwidth starved networks, and workload must be distributed among levels [32].

OpenFog's pillars, along with the IIoT, seemingly hold great promise for this, at least if they are designed considering the grid's requirements [10,14,18], as explained next. We note that designing a managed WAN system with QoS is very different from designing one over a LAN or even a MAN [33].

III. Fog Pillars for Electric Grids

The following pillars from the OpenFog Reference Architecture seem [34] are crucial for power grids (we note that there is some overlap between pillars):

Security: this is well-recognized as an absolute requirement since 9/11 and increasingly since the Ukraine hacking incidents in December 2015 [35,36,37,38]. Other than well-known CIA security triad, attestation seems particularly important, and possibly also non-repudiation for some apps.

Scalability: both the performance and reliability must be scalable with localized control at the edges. Localized state estimation and command and control aspects can be distributed to fog-enabled routers' coprocessors. In this manner, optimal (or close) solutions can be deployed without centralized management, which gives the potential for much more adaptability.

Autonomy: localized decisions by edge-hosted applications and services can manage their portion of sensor data flows, coprocessor configurations, etc. "Data gathered becomes Information when stored and retrievable becomes Knowledge. Knowledge enables Wisdom for autonomous IoT." [34]. This principle is the basis for localized analytics to enable autonomous decision making nearest the edge.

Programmability: applications and services should be able to be start, and stop on demand as configured by grid-specific requirements-drive management systems. Part of this involves an app discovering its environment and its location (both cyber and physical) in the grid.

Hierarchy: The problem should be decomposed into multiple layers, with more data available (or at least discoverable) as you go higher in the hierarchy. However, lower layers must be able to adaptively reconfigure if a given layer is unreachable, crashed, or under attack. Lower layers allow for a much faster response (sub-millisecond potentially if in a substation) with less global (or even regional) data.

Researchers have been proposing hierarchical approaches to power grid computations in recent years [29,39,40,41], but few are deployed yet (The algorithms in [40] are being deployed at Pacific Gas & Electric in the San Francisco area). Fog computing could enable an exponential increase of such deployments over the next decade.

RAS: reliability, accessibility, and serviceability mean selecting a new leader if one fails; restarting a node if a security breach is suspected, automated installations, etc. Managed reliability of distributed embedded edge systems is built through fault tolerance and autonomous resilience capabilities [42]. NOTE: a RAS in OpenFog nomenclature is very different from a RAS in the power grid: the latter is explained below and has the most extreme delay requirements over wide areas for the entire power grid [15].

IV. Candidate Algorithms for Edge Services

A. *ICT Platform Services*

Platform services are essential to map the potential of advanced ICT capabilities up to the power application level, via middleware [5].

GridStat: is a real-time publish-subscribe middleware framework designed from the ground up to deliver extremely low latencies (no more than ~1 msec over the speed of light across an entire power grid) even in the face of failures [14]. Its data plane is a graph of rate-based forwarding engines (FEs) that forward based on the middleware-level sensor data item and the subscribers that need it at a given rate by downsampling to a lower rate (i.e., dropping some updates) when a higher rate is not needed on a given outgoing link. Its management plane accepts subscription requests (with QoS+ of {rate, latency, #paths}, both desired and worst case) and tightly manages the data plane.

GridStat is also designed to be able to overlay not just a managed WAN consisting of GridStat Forwarding Engines but also other existing power communications infrastructures; utilities rarely have “green field” opportunities. GridStat has been under development at WSU since 2001, with live utility data since 2003, and experiments between national energy labs since 2008.

DCBlocks: as explained below, more and more power algorithms are getting decentralized, and they tend to involve coordination between remote computers. Fortunately, computer scientists have been working on distributed coordination problems since the late 1970s [20]. Unfortunately, the typical power app programmer has a BSEE degree with one C/FORTRAN and one MATLAB class; they have not heard about the field of “distributed computing”. Worst, many of the distributed coordination algorithms in the computer science literature seem to never have been programmed: they are written more to impress a theoretically-oriented colleague.

Thus, WSU began design of the DCBlocks platform in 2014. It aims to package up and make accessible the wealth of distributed coordination algorithms, as well as allowing new ones to be employed. Its goals include providing multiple implementations of a given “block” (distributed coordination problem) with different tradeoffs and even different failure assumptions [21]. Multiple power algorithms have been designed, implemented, and evaluated with DCBlocks, as cited above in this paper.

B. *Power Services*

There are a number of algorithms that can be deployed in edge services that are used by other power applications; we call these *power services*.

Synchrophasor Estimation: Traditionally, synchrophasors’ estimations are performed in a dedicated digital hardware devices installed at a substation. Analog current measurements from current transformers (CT) and voltage measurements from potential transformers (PT) are sampled and processed by an estimation algorithm and time stamped by a GPS signal to generate synchrophasors measurements typically at 30-60 Hz reporting rate. Fog devices can be used to run filtering and estimation algorithms to generate synchrophasors output given ability to synchronize with GPS signal and interface with analog current and voltage signals.

Phasor Data Concentrator/Processor (PDC) with bad data detection and data compression: Edge devices can also be used to collect synchrophasors measurements and time-align it to work as phasor data concentrator. Additionally, bad data detection algorithm can be deployed at PDC to filter out bad data or flag bad data. If needed, data can also be compressed before sending to decentralized or centralized synchrophasors applications.

Alarm Processing: when grid conditions are becoming bad many alarms are raised. They go to the control center where they are tabulated in a simple fashion. Pushing alarm processing to the edges would help reduce the load on the control center. It also could enable grid topology to be associated with given alarms much more readily.

C. Power Applications

Distributed State Estimation: Traditional centralized state estimation may not run as fast to provide 'clean measurements' for some of the distributed applications. Additionally, centralized state estimation may not converge and not robust causing problems to loose situational awareness of the complete system. Distributed state estimation can be implemented using multiple edge computing devices and utilizing distributed computing algorithms which provides a) partial situational awareness of the system given non-convergence of one of the cluster in the electric grid, b) computational robustness inherently provided by fault-tolerant distributed computing, c) faster convergence and ability to provide 'clean measurements' at much faster rate to support distributed/ decentralized applications.

Distributed Voltage Stability: Voltage stability is a local problem initially and slowly expands to throughout the power grid if not controlled. Voltage stability monitoring and control is inherently suitable for decentralized/ distributed computation and more efficient to take control action in time before voltage stability impacts at the wider level. Edge computing devices can be utilized for voltage stability assessment using measurements only for rough estimation of voltage stability or integrated with distributed state estimation to deploy hybrid voltage stability estimation. Data utilized for distributed voltage stability assessment can be dynamically changed based on voltage sensitivity and a suitable control action can also be computed based on the status of reactive power devices or voltage control devices.

Distributed Power flow management: In some windy areas, we could image a local control coordinating actions in a group of substations hosting wind power farms. This control could take advantage of dynamic line ratings and could act on beakers in order to minimize wind power curtailments. The kind of application is certainly feasible and could be implemented through a Model Predictive Control approach using a middleware which guarantees the required reliability level of data delivery and coordination. This is an example how a digital solution could avoid overinvestment in grid assets.

Remedial Action Schemes (RAS): Remedial actions schemes (RAS) are generally last resort and critical to prevent system instability/ possible cascading outage to minimize the impact of adverse events or operating scenarios. RAS is generally implemented using substations devices and can be supported by edge computing devices to compute the control actions. Additionally, edge devices can be coordinated using fault-tolerant distributed computing for computational robustness to guarantee solutions when needed.

Load Modeling and Power Component Behavior: Load behavior can be tracked in real time to analyze the impact of changing voltage on power consumption, analyzing possible fault induced delayed voltage recovery or voltage instability. Existing operating practice assumes conservative model for the loads (constant power) for voltage stability studies. Tracking load behavior and expected impact on power consumptions with changing voltage will help in number of applications including estimating the power transfer limit more accurately and hence saving of millions of dollar for economic operation. Edge devices can be used to track load models using voltage and power measurements at substations. Similar concepts can also be applied to track behavior of other devices in real time specially power electronics devices with changing control mode and hence better analysis for expected behavior of the system.

Distributed Applications in Microgrid/ Active Distribution System: With integration of renewable energy, battery and demand response, number of state variables and control variable has exploded. Existing operational algorithm are not scalable and need to be processed in hierarchal manner and coordinate with distribution management system (DMS). This problem becomes more challenging: as distributed energy resources (DERs) are owned by different organizations/ entities. Edge computing devices can be deployed in active distribution system for coordinated control of voltage, frequency and power and utilize DERs in much more efficient way.

Future Decentralized Applications: It is inevitable that the recent trend towards decentralized power algorithms will continue [20]. Voltage and frequency control in the existing grids are designed assuming a passive distribution system. With integration of different types of distributed energy resources (DER) and associated control, voltage control is challenging as embedded control in DER responds back to centralized or local control causing problems in maintaining voltage within limit with variance in DER participation. Additionally, as DER replaces conventional rotating machines with high rotational inertia, frequency control will be increasingly harder. DER offers opportunity to provide frequency support with additional control mechanism but requires coordination and top-level hierarchal control. Given the scale of number of variables involved, developing decentralized coordinated control will be necessary enabled by edge computing.

V. TESTBED

WSU's Smart Grid Demonstration and Research Investigation Lab (SGDRIL) is fully equipped for developing smart grid applications in a representative substation ICT environment [43]. This unique cyber-physical lab is equipped with a variety of power and industrial control devices from multiple vendors, including many devices from the local Schweitzer Engineering Laboratories (SEL).

Simulated grid readings are created by a Real Time Digital Simulator (RTDS) and the Opal-RT simulator, whose signals are passed through Ponovo Digital Simulator Amplifiers which is then measured by SEL, Alstom, and ERL Phasor Measurement Units (PMUs) as well as PT/CTs and GE Line Distance Relays. Phasor measurements and other digital signals are also directly sent out over the network to a variety of ICT components.

These ICT control devices take a variety of forms, including SEL substation computers, beagle board microcontrollers, and Cisco Fog equipped routers. The cisco control devices take a variety of forms, including the Connected Grid Router 1120, Industrial Ethernet 4000 switch, and two Industrial Service 809 routers. Each of these are equipped with virtual computing environments for application deployment, and are managed by a terminal server. Both GridStat and DCBlocks are installed in SGDRIL and have been used for a number of cyber-physical ICT-power experiments.

Together these devices form the SGDRIL, and are the majority of control components in a substation plus simulators to inject realistic power data in real-time and in the power protocols used by the ICT control devices, PMUs, and PDCs.

Figure 1: SGDRIL Testbed

VI. Conclusions and Future Work

Fog computing, working with or without the Cloud, has great potential to improve the power grid's stability by making it more flexible, dynamic, and manageable. In this paper we have explain the basics of the power grid and opportunities for better ICT to help the grid via Fog technology.

Future work will involve deploying and evaluating all of the candidate edge applications in the fog, plus others, and working on power-appropriate management system for these. As part of this, new architectural possibilities for the grid will emerge, enabled by the Fog and almost certainly also the Cloud.

A longer version of this paper, with active hyperlinks to references, can be found at GridICT.net.

More case studies can be found in the following Cisco documents on utility customer stores [44] and the NeoSilica case study for the internet of things. [45] Both of which highlight ways Cisco is working to advance IoT for the utility sector. More use cases of edge/fog computing can be found in [46].

Acknowledgement

We thank RTE France for initiating this investigation, and for providing initial funding. We thank the Power Systems Engineering Research Center for managing the project via Project S-63G. We thank Cisco's university research grant program for a recent donation.

References

[1] "What Would Edison Think of Today's Energy Grids?", Energy Central, July 10, 2017.

[2] "Grid 2020: Towards a Policy of Renewable and Distributed Energy Resources", Resnick Institute Report, Caltech, September 2012.

[3] "Southern California Smart Grid Research Symposium in Review", 2011,–Resnick Institute Report, Caltech, September 20111.

[4] "NASPI 2014 Survey of Synchrophasor System Networks — Results and Findings", NASPI Technical Report, July 2015.

[5] David E. Bakken, Richard E. Schantz, and Richard D. Tucker. "Smart Grid Communications: QoS Stovepipes or QoS Interoperability", in *Proceedings of Grid-Interop 2009*, GridWise Architecture Council, Denver, Colorado, November 17-19, 2009.

[6] Y.Wu, L. Nordstrőm, and D. Bakken. "Effects of Bursty Event Traffic on Synchrophasor Delays in IEEE C27.118, IEC61850, and IEC60870", in *Proceedings of the Sixth IEEE International Conference on Smart Grid Communications (SmartGridComm 2015)*, Miami, Florida, November 2–5, 2015.

[7] A. Srivastava, C. Hauser, D. Bakken, and A. Hahn. *Cyber Infrastructure for the Smart Electric Grid*. Wiley, 2018, to appear.

[8] Daniel Germanus, Ioanna Dionysiou, Harald Gjermundrød, Abdelmajid Khelil, Neeraj Suri, David E. Bakken, and Carl Hauser, "Leveraging the Next-Generation Power Grid: Data Sharing and Associated Partnerships", *IEEE PES Conference on Innovative Smart Grid Technologies Europe*, October 10-13, 2010 Chalmers Lindholmen, Gothenburg, Sweden.

[9] Root, C. The Future Beckons, IEEE Power & Energy Magazine, 4(1), January/February 2006, 24–31.

[10] Carl Hauser, David Bakken, and Anjan Bose. "A Failure to Communicate: Next-Generation Communication Requirements, Technologies, and Architecture for the Electric Power Grid", *IEEE Power and Energy*, 3(2), March/April, 2005, 47–55.

[11] Cleveland, F. IEC TC57 Security Standards for the Power Systems Information Infrastructure — Beyond Simple Encryption, IEC TC57 WG15 Security Standards White Paper, 2007.

[12] Pourbeik, P., Kundur, P, and Taylor, C. —The Anatomy of a Power Grid Blackout, *IEEE Power & Energy Magazine*, 4(5), September/October 2006, 22–29.

[13] David E. Bakken, Carl H. Hauser, Harald Gjermundrød, Anjan Bose, "Towards More Flexible and Robust Data Delivery for Monitoring and Control of the Electric Power Grid",. *Technical Report TR-GS-009*, School of Electrical Engineering and Computer Science, Washington State University, May 2007.

[14] D. Bakken, A. Bose, C. Hauser, D.Whitehead, and G. Zweigle. "Smart Generation and Transmission with Coherent, Real-Time Data. *Proceedings of the IEEE*, 99(6), June 2011, 928–951.

[15] Gregary Zweigle. "Emerging Wide-Area Power Applications with Mission Critical Data Delivery Requirements", in *Smart Grids: Clouds, Communications, Open Source, and Automation*. David Bakken and Kris Iniewski, editors CRC Press, 2014.

[16] David Bakken, Harald Gjermundrød, Ioanna Dionysiou. "GridStat: High Availability, Low Latency and Adaptive Sensor Data Delivery for Smart Generation and TransmissionF", in *Smart Grids: Clouds, Communications, Open Source, and Automation*. David Bakken and Kris Iniewski, editors CRC Press, 2014

[17] Sanjay Goel and David Bakken. Smart Grid of the Future: Vision for year 2030. In *Smart Grid of the Future: Vision for Year 2030*. IEEE Communications Society, Sanjay Goel, Stephen Bush, and David Bakken (eds), 2013.

[18] David E. Bakken and Carl H. Hauser and Harald Gjermundrød, "Delivery Requirements and Implementation Guidelines for the NASPInet Data Bus", in Proceedings of the First IEEE International Conference on Smart Grid Communications (SmartGridComm 2010), IEEE, Gaithersburg, MD, Oct 4–6, 2010, 37–42.

[19] Robert Wojcik and AndreJ Jajszczyk, "Flow Oriented Approaches to QoS Assurance", *ACM Computing Surveys*, 44(1), January 2012.

[20] Banerjee, P., S. Niddodi, H. Lee, A. Srivastava, and D. Bakken, 2015: On the need for robust decentralized coordination to support emerging decentralized monitoring and control applications in electric power grid. Proceedings of the Fourth Grid of the Future Symposium, CIGRE, Chicago, October 14-15, 2016, USA, 1–9.

[21] Shwetha Niddodi, Decentralized Coordination Building Blocks (DCBlocks) for Decentralized Monitoring and Control of Smart Grids, WSU MS Thesis, December 2015.

[22] V. Krishnan, R. Liu, A. Askerman, A. Srivastava, D. Bakken, and P. Panciatici. "Fault-Tolerant Distributed Computing for Remedial Control Action with Wind Energy", in Eighth ACM International Conference on Future Energy Systems (ACM e-Energy), Hong Kong, May 17-19, 2017.

[23] V. Krishnan, R. Liu, A. Askerman, A. Srivastava, D. Bakken, and P. Panciatici, "Resilient Cyber Infrastructure for the Minimum Wind Curtailment Remedial Control Scheme", in *Proceedings of the 2017 IEEE Industry Applications Society Annual Meeting*, Cincinnatti, Ohio, USA, October 1-5, 2017, to appear.

[24] Ren Liu, Anurag Srivastava, Alexander Askerman, David Bakken and Patrick Panciatici, "Decentralized State Estimation and Remedial Control Action for Minimum Wind Curtailment Using Distributed Computing Platform", in *Proceedings of the IEEE Industrial Application Society Annual Meeting*, Portland, October 2016.

[25] Ren Liu, Anurag Srivastava, Alexander Askerman, David Bakken and Patrick Panciatici, "Decentralized State Estimation and Remedial Control Action for Minimum Wind Curtailment Using Distributed Computing Platform", *IEEE Transactions on Industry Applications*, 2017, to appear.

[26] Hyojong Lee, Shwetha Niddodi, Anurag Srivastava, and David Bakken. "Decentralized Voltage Stability Monitoring and Control in the Smart Grid using Distributed Computing Architecture", in *Proceedings of the 2016 IEEE Industry Applications Society Annual Meeting (IAS)*, Portland, OR, 2-6 October, 2016.

[27] K. Birman, L. Ganesh, R. van Renesse. "Running Smart Grid Control Software on Cloud Computing Architectures", in Proceedings of the Workshop on Computational Needs for Next Generation Electric Grid, Cornell University, Ithaca, NY, April 19-20, 2011.

[28] David Bakken, Mani Venkatasubramanian, Anurag Srivastava, Yilu Lui, Anjan Bose, Santiago Grijalva. "Power Application Possibilities for Cloud Computing", in *Smart Grids: Clouds, Communications, Open Source, and Automation*. David Bakken and Kris Iniewski, editors CRC Press, 2014.

[29] L. Tang and P. Sauer, "Cloud and Information Hierarchy for a Future Grid", Power Systems Engineering Research Center, PSERC Publication 12-03, June 2013.

[30] Thoshitha Gamage, David Anderson, David Bakken, Ken Birman, Anjan Bose, Carl Hauser, Ketan Maheshwari, and Robbert van Renesse. "Mission Critical Cloud Computing for Critical Infrastructures", in *Smart Grids: Clouds, Communications, Open Source, and Automation*. David Bakken and Kris Iniewski, editors CRC Press, 2014.

[31] Cloud Data Sharing Platform: Final Project Report (S-67G), Power Systems Engineering Research Center, 2016.

[32] K. Bierzynski, A. Escobar and M. Eberl, "Cloud, fog and edge: Cooperation for the future?," *2017 Second International Conference on Fog and Mobile Edge Computing (FMEC)*, IEEE, Valencia, Spain, 2017, pp. 62-67.

[33] Zinky, J. and Bakken, D. and Schantz, R., —Architectural Support for Quality of Service for CORBA Objects,*Theory and Practice of Object Systems*, 3:1, April 1997, 55–73.

[34] OpenFog Consortium, "OpenFog Reference Architecture for Fog Computing", February, 2017.

[35] "Roadmap to Achieve Energy Delivery Systems Cybersecurity", US DOE, September 2011.

[36] Bakken, D. and Bose, A. and Bhowmik, S. "Survivability and Status Dissemination in Combined Electric Power and Computer Communications Networks", in *Proceedings of the Third Information Survivability Workshop* (ISW-2000), CERT, October, 2000, Boston, MA.

[37] Bakken, D., Evje, T., and Bose, A. "Survivable Status Dissemination in the Electric Power Grid", in *Proceedings of the Information/System Survivabilty Workshop*, in *Supplement Proceedings of the International Conference on Dependable Systems and Networks (DSN-2001)*IEEE/IFIP, Göteberg, Sweden, July 2001.

[38] Hauser, Carl H., Bakken, David E., Dionysiou, Ioanna, Gjermundrød, K. Harald, Irava, Venkata, Helkey, Joel and Bose, Anjan. "Security, Trust and QoS in next-generation control and communication for large power systems," *International Journal of Critical Infrastructures*, Inderscience, 4(1-2), 2008, 3–16.

[39] M. Seewald and J. Taft. "Distributed Control for DER and Distribution Automation", Protection Automation & Control World (PACWorld), September 2013.

[40] T. Yang, H. Sun, and A. Bose. "Transition to a Two-Level Linear State Estimator—Part I: Architecture", *IEEE Transactions in Power Systems*, 26(1), 2011, 46–53.

[41] R. Zamora and A. Srivastava, "Multi-Layer Architecture for Voltage and Frequency Control in Networked Microgrids", *IEEE Transactions on Smart Grid*, July 2016.

[42] A. Dubey, G. Karsai and S. Pradhan, "Resilience at the edge in cyber-physical systems,"*2017 Second International Conference on Fog and Mobile Edge Computing (FMEC)*, Valencia, Spain, 2017, pp. 139-146.

[43] "Smart Grid Demonstration and Research Investigation Lab." Smart Grid Demonstration and Research Investigation Lab | Smart Grid Demonstration & Research Investigation Lab (SGDRIL), Washington State University

[44] "Customer Stories - Electra Case Study." Cisco, Cisco

[45] "Internet of Things: Driving Digital Transformation." Cisco, Cisco,.

[46] Clifton Black, "Fog Computing in Energy Environments", in *Proceedings of the Fog World Congress*, IEEE and OpenFog Consortium, Oct. 30 to Nov. 1, Santa Clara, California.