1

IEEE PES Emerging Technologies White Paper 2019

Edited by the Intelligent Grid and Emerging Technologies Coordinating Committee.

***Abstract* — This white paper identifies and provides information on emerging technologies related to technical fields of the IEEE Power and Energy (PES) Society. Another purpose is to provide input to the IEEE PES leadership and thus assist in setting priorities for the PES technical activities and keep informed PES and other IEEE members interested in any of the IEEE PES technical fields. These goals are achieved through organizing committee meetings, panel and paper sessions at the annual IEEE PES General Meetings (and other conferences), communication with the standing PES Technical Committees, discussions with experts in particular fields of interest, and other activities. This paper is prepared as a starting point of an evolving document that would track new developments related to emerging technologies of interest to PES.**

***Index Terms*—Electric power systems, electric energy, emerging technologies, smart grid.**

I. Introduction

THE oldest society of the Institute of Electrical and Electronics Engineers (IEEE) is the Power & Energy Society (PES), formerly known as the IEEE Power Engineering Society, is focused on the scientific and engineering knowledge related to electric power and energy. Its goal is to be the leading provider of such knowledge for the betterment of society and for the professional development of its members. The PES is the world's largest forum for sharing the latest information about technological developments in the electric power industry, for developing standards that guide the development and construction of equipment and systems, and for educating members of the industry and the general public [2]. PES members are leaders in this field; they create and derive substantial benefits from involvement with this unique and outstanding professional technical association.

The mission of PES is: To be the leading provider of scientific and engineering information on electric power and energy for the betterment of society, and the preferred professional development source for our members [2]

The scope of the Power and Energy Society embraces research, development, planning, design, construction, maintenance, installation and operation of equipment, structures, materials and power systems for the safe, sustainable, economic and reliable conversion, generation, transmission, distribution, storage and usage of electric energy, including its measurement and control [2].

In the modern world with its rapid, continual development of new technologies, tracking new developments related to emerging technologies of interest to PES is not a trivial task. In addition to PES Technical Committees, the PES has paid special attention to the task of tracking emerging technologies by creating an Emerging Technologies Coordinating Committee (ETCC). The ETCC sponsored a Technology Assessment Working Group (TAWG) which was primarily concerned with collecting information on emerging technologies, assessing their potential impact on PES, and preparing periodic reports. Since expansion in Jan. 2016, this work has been performed by a joint Intelligent Grid and Emerging Technologies Coordinating Committee (iGETCC).

This paper is conceived as an evolving document that will track new developments related to emerging technologies of interest to PES members. The intent is to use this format to share the information and evaluations collected by the iGETCC with interested PES members and others in the electric power community.

II. Important Definitions

Early on in the work of ETCC and iGETCC, it became obvious that in the discussions of the participants and in the written contributions, terms describing emerging technologies and technology applications were often defined inconsistently across sources, mixed-up, and used inconsistently. To make a distinction between a technology and its initial applications, it was necessary to introduce some simple but clear definitions of the basic terms that were in frequent use.

Technology can be broadly defined as “the application of scientific knowledge to the practical aims of human life” [3], especially to industrial or commercial objectives. "Technology" can refer to material objects of use to humanity, such as machines, hardware or utensils, but can also encompass broader creations, including systems, methods of organization, and techniques [4].

Example 1: **Synchrophasor measurement technology**: Hardware and methods for calculating phasors from time-stamped signal samples.

Example 2: **Sensor technology**: Devices and methods for measuring physical quantities such as current, voltage, temperature, speed, vibration, etc.

Technology application can be defined as an act of putting a technology to use, and a use to which a specific technology is put [5].

Example 1: **Fault location**: Use of synchrophasor measurement technology to locate faults in power systems.

Example 2: **Thermal protection of transformers**: Use of temperature sensor technology to determine critical temperatures of transformers.

Where it was possible or practical, the following items have been included in the consideration of each emerging technology:

- Emerging Technology Name
- Brief Technology Description
- Technology Application(s)
- Technology Benefits
- Challenges, Barriers, Gaps
- Status – Trends, Installations
- Standards Work
- Potential Impact on Power & Energy Systems
- References

These requirements were seen as demanding by a number of potential and actual information contributors, but they helped in distinguishing technologies from applications of technologies, as well as in getting a clearer picture of the status and potential applications of each emerging technology.

III. PES Related Emerging Technologies

The following is a non-exhaustive list of PES-related emerging technologies, arranged so as to approximately reflect the fields of work of the PES Technical Committees. In several cases, the related PES Technical Committee is a source of the information provided here.

A. Electric Machinery

Technology: High Temperature Superconductor (HTS) Power Equipment.

Description: Superconducting Power Equipment for use in wind power systems for either or both motors and generators, High Temperature Superconductors (HTS) used for the field winding, while the armature winding is always made of copper. Transformers, power transmission cables, and fault-current limiters employing superconductors have been demonstrated worldwide.

B. Energy Development & Power Generation

Technologies: mainstream: solar (photovoltaic, concentrating, thermal), wind, water, biomass, waste, hydro (large, small), ocean power (wave and tidal).

Renewable Energy

Technologies:

- Biomass Energy
- Biofuels: ethanol, made primarily from the starch in corn grain; biodiesel, made primarily from soybean oil.
- Geothermal Energy (geothermal or ground-source heat pump, GHP)
- Hydrogen
- Hydropower
- Ocean Energy
- Solar Energy
- Wind Energy
- Renewable Natural Gas (RNG)

Low Impact Hydropower [6] - Hydroelectric facilities that meet certain criteria (impact on river flows, water quality, fish passage and protection, watershed protection, threatened and endangered species protection, cultural resource protection, and recreation) to minimize their effects on rivers, fish, and wildlife under a voluntary certification program developed by the Low Impact Hydropower Institute (LIHI).

Ocean Energy[7]-[9]

Technologies: Ocean Thermal Energy Conversion (OTEC), Tidal Power, Wave Power.

Subcategories:

- Ocean Thermal Energy Conversion (OTEC)
- Closed-Cycle
- Open-Cycle
- Hybrid
- Tidal Power (Hydrokinetic Energy - wave energy converters, WECs, or rotating devices.)
- Barrage or dam
- Tidal fence
- Tidal turbine
- Wave Power (Hydrokinetic Energy)
- Offshore Systems
- Point Absorbers/bobbing motion of the waves to power a pump that creates electricity
- Attenuators/heave-surge devices that use hoses connected to floats that ride the waves.
- Overtopping devices/seagoing vessels/floating platforms capture the energy of offshore waves by funneling waves through internal turbines
- Onshore Systems extract the energy in breaking waves
- Oscillating water column
- Tapchan, or tapered channel system
- Pendulor wave-power device

Hydrogen

Technology: Hydrogen as an important energy carrier/storage buffer (current nascent markets: continuous duty fork-lifts, baggage carriers at airports, back-up power for remote cellular tower sites).

Reforming - separation of hydrogen from hydrocarbons through the application of heat. Currently, most hydrogen is made this way from natural gas.

Electrolysis - separation of hydrogen from water through the application of electrical current.

Currently, hydrogen has great potential as a power source for fuel cells.

C. Insulated Conductors

Technologies: nano-dielectrics, high-voltage power supplies and other devices for under-sea applications (e.g. for oil drilling purposes), more precise detection and location of partial discharges in complex insulation systems and using their analysis for identification of defects, continue to be one of diagnostic efforts.

D. Power System Analysis, Computing and Economics

Technologies: Energy Information Systems (EIS)/Web-Based Energy Management Systems; software tools for real-time grid reliability management; price responsive load; Consortium for Electric Reliability Technology Solutions (CERTS) microgrid; Simulation/Modeling Tools (Graph Trace Analysis, GTA, an application - not really a technology). [10]

Energy Information Systems (EIS) have greatly benefited from Information Technology (IT) developments, cheap communication equipment, and new reliable wired and wireless communication technologies. As with most new scientific and engineering advances, it is often not immediately clear which parts of a power system can benefit from this new technology. A few areas have emerged as potential benefactors of these IT developments. Demand monitoring and management is one of the more interesting applications due to potential energy and cost savings. EIS allow for demand and generation control at different levels of transmission and distribution systems. Web energy management is usually associated with remote monitoring and control of building or enterprise-wide energy consumption. A microgrid serves a larger consumer such as a university campus with generation and or cogeneration capabilities, and smart grids are usually defined at the utility distribution system level.

Description: Web energy management system can handle from a single demand to a very large number of monitored loads. The demand can be monitored, power consumption can be rescheduled based on the collected data, or the communication between supplier and customer can be bidirectional. The common, underlying idea is to access monitoring sensors and control devices remotely over the internet. The communication medium used is not significant as long as it provides sufficient bandwidth for the degree of control required and uses standard TCP/IP stack implementation.

EIS/EMS tools enable demand to be controlled in real time either manually or automatically. Microgrids must schedule both demand and generation output. Smart grids can be a complex and therefore confusing approach to energy management. Smart grids can be implemented and run by an entity that is completely separate from energy generation, distribution, or consumption by connecting and optimizing the operation of these individual parts of the power system to achieve some predefined goal.

Applications: The applications derived from these energy approaches are varied and flexible, since they are software based. There are a few different companies marketing web energy management packages. Microgrids controllers are not as common, due in part to market and regulatory issues yet to be resolved. The potential of smart grids, including microgrids, are still not fully quantified, although they are estimated to be large and valuable to both power system operators and their customers.

Benefits: The main goal of EIS is energy savings leading to consumers' savings, peak load shaving, delaying distribution system investment into new wires, and transmission system reliability improvements through demand control.

Challenges, Barriers, Gaps: Most of barriers faced by the EIS are defined by the goals any given application is intended to achieve. EIS could, in concept, be used for dynamic control, but this requires currently unattainable communication speeds. Today's communication bandwidths are generally satisfactory for energy management purposes, but there is a major lack of implementation knowledge in this area. The operation of web energy management systems and microgrids must be integrated into the larger utility grid systems if the potential savings in power, greenhouse gas emissions, and costs are to be achieved. There are currently no fully-realized microgrid control implementations. Even when unlimited communication bandwidth, detail-level demand monitoring, and automated demand control systems are available, it is not yet clear how interested parties can take appropriate advantage of the combination of these technology advances. This situation is due, in large part, to gaps in the regulations. Regulators are aware that there should be demand control and demand shifting but they fail to define who should do it and how they would be compensated for those efforts. Utilities are in the best position to implement and benefit from these EIS and demand management but it is not clear if and how the rest of the industry, including the customers, would benefit at the same time.

Status, Trends, Installations: Most of the efforts are currently in local, building or microgrid control areas. There is significant R&D in the area of microgrid implementation and even some working demonstration sites. A list of hardware developers and implementers is given in the references.

Standards Work: IEEE 1547 Series Standards, IEEE 1547–2018 Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE 1547.4–2011 Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems.

Potential Impact on Power Industry: Impact on the power engineering and power industry is twofold. Usage of

EIS helps users control their demand at the local level and will eventually allow for coordinated control of entire distribution systems to lower the demand when needed. Also, widespread implementation of demand control will result in much smaller margins for distribution system reliability, which will not be a good consequence.

E. Power System Communications

Technologies: Wired Communications in Digital Substations – Ethernet (IEC 61850, IEC 61869), Resilient Packet Ring (RPR), Broadband over Power Line; Wireless Communications - short range (Zigbee, LoPan, Zwave, etc.), medium range (WiFi), long range (WiMax).

F. Power System Relaying

Technologies: Synchronized sampling, wide-area protection.
Description: Synchronized phasor technology has been used primarily in Phasor Measurement Units (PMUs); synchronized sampling technology has been recognized only recently. The two technologies look much alike. The main difference is in their focus: synchronized phasors are obtained by time stamping calculated phasors obtained from an IED using GPS time reference; synchronized sampling clocks in IEDs use the Pulse per Second (PPS) time reference from the GPS receivers. The difference is in the applications; synchronized samples allow for straightforward differentiation of phase differences among channels, while determining the same from scanned values can involve complex computations. The requirement for phase angle differentiation among the three phases for fault detection and classification precludes the use of scanned data from Remote Terminal Units (RTUs) of existing Supervisory Control and Data Acquisition (SCADA) systems . Typical examples of synchronized sampling are Digital Fault Recorders (DFRs), Digital Protective Relays (DPRs) and Circuit Breaker Monitors (CBMs). Since synchronized sampling may be used to calculate synchronized phasors, it may be considered a broader concept than synchronized phasors.

G. Electric Energy Storage (excluding thermal storage)

Technologies: Pumped storage hydro (PSH), compressed air energy storage (CAES), conventional batteries (lithium ion), high-temperature batteries (sodium-Sulphur, sodium-nickel chloride), flow batteries (regenerative fuel cells), flywheels, electric double layer capacitors (EDLC), superconducting magnetic energy storage (SMES).

Technology Name: Super Conducting Magnetic Energy Storage (SMES)

Description: Energy storage based on high temperature super conductors and the characteristics of inductors. The system used liquid nitrogen to hold electricity in the coils until it is needed by the grid. Control system provide the ability to either cause the system to charge or discharge.

Applications: Fast response ancillary services are the initial application for SMES, given current pre-commercial unit sizes, frequency and voltage support are currently the targeted uses. For manufacturers that need high power quality and very stable voltage and frequency – SMES is a reasonable choice.

Benefits: SMES has no memory effect and can be operated hundreds to thousands of times a day. The system has no moving parts, so maintenance of the storage unit is minimal. Units of 1 MVA are of a size that can fit into a typical existing substation. Because the power is stored as A/C power, conversion losses to and from storage is less than other storage units.

Challenges, Barriers, Gaps: SMES units get physically large fast as heir capacity increases. A 1 GW unit built with today's technology would be miles on a side. These units need liquid nitrogen to operate, meaning regular deliveries of cryogenic gasses are required. Operating experience is limited, so what SMES units will eventually do needs time to determine.

Trends, Installations: At least 2 major manufacturers are building low rate, commercial units. Less than 10 units have been installed to date.

Standards Work: Safety, material, and operations standards will need to be developed.

Potential Impact on Power & Energy Systems: SMES could remove most spinning reserve units from the grid over time, and could smooth out cloud transients and other power quality issues.

Technology Name: Renewable Natural Gas (RNG) [41]

Description: Energy storage using methane. Water and CO2 are broken down and the resulting hydrogen and carbon are combined to make natural gas. Electricity is used do the chemical work.

Applications: Storage of potentially large amounts of energy for long term storage. It reuses existing storage and pipeline assets, as well as customer assets like stoves and furnaces.

Benefits: High reuse of existing assets and few issues with the technology.

Challenges, Barriers, Gaps: RNG is energy negative – more energy in than energy out with current RNG being about 50% efficient in a round trip.

Trends, Installations: RNG is one of the products of metal-organic frameworks.

Standards Work: Conversion plant safety.

Potential Impact on Power & Energy Systems: RNG, if it reaches wide scale use, would greatly increase the percentage of solar and wind that the grid could handle because of the decoupling of energy production and energy use.

Technology Name: Cryogenic Air Storage (RNG) [42]

Description: Energy storage using liquid air. The phase transition from liquid to gas expands volume by 700 times, providing pressure and velocity to turn air turbines which generate electric power.

Applications: Potentially large, long-term storage of energy. Collecting the helium and other high-value, low-volume gasses as the air is liquified could create an additional revenue stream for the owners of this type of energy storage system.

Benefits: Environmentally friendly, non-toxic, storage medium. This technology is currently used by liquid air plants worldwide.

Challenges, Barriers, Gaps: Cryogenic storage has challenges with energy use vs. energy output. Liquid air plants can be noisy, restricting where they can be located.

Trends, Installations: The UK has recently installed their first plant for the purposes of energy storage.

Standards Work: How to characterize this technology for energy use and production, including ramp rates.

Potential Impact on Power & Energy Systems: Potential for a fast ramping storage facility that can offer storage for hours to days at a time. It may be able to replace batteries in some instances.

H. Smart Grid (SG)

Technology: Smart Grid [11]-[15]
Description: Although presently there is no single accepted definition of Smart Grid (SG means different things to different people), the term refers to electrical power system and technologies that allow two-way energy flow registration and monitoring (Smart Metering; Advanced Metering Infrastructure, AMI) and connection of both user loads and user energy sources (usually renewable energy sources: solar, wind, etc.) to the electrical power grid. The goal is improved efficiency, power quality, reliability, and security of the future electrical power system at both the transmission and distribution levels, achieved by adding communications and networking capability, automation, and intelligence in many forms.

US National Energy Technology Laboratory (NETL) [16] groups technologies that enable Smart Grid operation into five key areas: integrated communications, sensing and measurement, advanced components, advanced control methods, and interfaces and decision support.

In recent years, a new concept of "*transactive energy*" which envisions a more intelligent and interactive grid with improved efficiency and reliability has gathered a lot of attention. Transactive energy (TE) can be defined as "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using *value* as a key operational parameter" [17]. The Gridwise Architecture Council has published a Transactive Energy Framework [17], which provides TE definitions, attributes, principles, and guidelines. Transactive Energy also entails public policy, market design, business models, architecture guidelines, and infrastructure considerations. NIST has published Transactive Energy Modeling and Simulation Challenge for the Smart Grid [18].

There have already been successful transactive energy demonstration projects, such as the Pacific Northwest Demonstration R&D Project funded by U.S. Department of Energy (DOE) [19] and the gridSMART Demonstration Project implemented by AEP Ohio. These projects tested various new technologies for smart grid implementation on regional and local levels including smart meters, distribution automation, volt var optimization, consumer programs, plug in electric vehicles, and smart appliances [20]. In Europe, an Energy Flexibility Platform and Interface (EF-PI) has been explored. This is an open-source software platform that end users can use to communicate with, configure, control and monitor their own smart appliances [21].

I. Substations

Technologies: Gas-Insulated Transmission Lines (GIL).
Description: Gas-Insulated Transmission Lines (GIL) (e.g. gas mixture of nitrogen and SF6 for the 245 kV to 550 kV range ensure high transmission capacity, much better electromagnetic compatibility (EMC) than any other transmission system and flexible installation options - above ground, in tunnels, or buried in the soil. Future trends: off-shore wind parks with high power connection to the transmission grid; for rail and road transportation tunnels.

J. Switchgear

Technologies: Both SF6 and non-SF6 gasses can provide an arc-interrupting and dielectric medium in circuit breakers; circuit breakers based on power electronics; Silicon-Carbon (SiC) devices (diodes, transistors, etc.) for higher voltages and higher switching efficiencies; Custom Power Systems/Devices (power electronics in distribution systems up to 38 kV and in Distributed Energy Resources (DER) such as solar, wind, and energy storage systems); mainstream: SCRs and GTOs for transmission voltage and load control.

Technology Name: DC Switches and Breakers

Brief Technology Description: On both transmission and distribution sides there is a need for DC switching equipment. On the MV side, the need is driven by proliferation of distributed generation like PV solar that operates on DC, and for the large scale HVDC grid, it is important that any fault is isolated very rapidly before it affects the DC voltage in other parts of the grid.

Technology Applications: In distributed generation, on the DC side of storage, utility-scale wind and solar farms, HVDC transmission, DC distribution, Electric Vehicle (EV) chargers.

Technology Benefits: Fast isolation of DC faults, allowing arc-free switches within buildings, and minimizing potential damage to equipment.

Challenges, Barriers, Gaps: DC switches and breakers need to operate on a sub-cycle to protect equipment. They need to create an artificial zero crossing to minimize (hopefully prevent) arcing.

Status – Trends, Installations: There are currently 4 types of technology being researched:

1. using a passive oscillating principle
2. current oscillation scheme with active current creating artificial current zero:
3. injection, pure power electronic devices in the nominal current path,
4. built with hybrid mechanical and power-electronic combination [40]

Standards Work: Testing, safety, and application standards are all needed.

Potential Impact on Power & Energy Systems: These units are one of the areas that are holding back more DC use in the industry.

Technology Name: High voltage vacuum interrupter (VI)

Description: Vacuum Interrupters are replacements for portions of Gas Insulated Switchgear (GIS). VI were developed because of concerns about SF6's impact on the environment.

Applications: Vacuum interrupters have been used in Medium Voltage equipment for more than 50 years. A decade ago, in an effort to replace SF6 gas, a number of R&D projects started in Europe and China, which led to a number of new switchgear products for up to 145kV. [31] For higher voltage applications, two VIs were used in series connection in some cases.

Benefits: Other than environmental benefits, there are a number of technical advantages of using VIs over SF_6 breakers, including higher switching endurance, reduction of drive energy (more compact mechanism design), lower arc voltage and arcing time, and reduced maintenance.

Challenges, Barriers, Gaps: There are also some drawbacks; VIs have significantly higher number of re-ignitions in inductive load switching, can have random breakdown during BIL dielectric tests, may emit X-rays in open position during AC withstand testing, and it is harder to quality of interruption medium in case of SF6 breakers.

Status – Trends, Installations: VI are in production up to 145KV. Most installations to date are in China.

Standards Work: Replacement of GIS with VI standards and guidelines, safety, maintenance and testing.

Potential Impact on Power & Energy Systems: May eventually replace GIS switchgear.

Technology Name: Higher voltage solid dielectrics

Description: At the distribution level most equipment transitions to gas-insulated or air-insulated when the voltage exceeds 44KV. Higher voltage solid dielectrics offer the same type of low voltage reclosers and other equipment at 69KV and other sub-transmission voltages.

Applications: Switchgear, reclosers, and other distribution equipment.

Benefits: Common equipment, similar to what crews are used to installing similar equipment.

Challenges, Barriers, Gaps: Early tests on solid dielectrics were disappointing in the field. More recent work is promising.

Trends, Installations: Pilots are underway in 69KV.

Standards Work: Updating switchgear and other standards for the higher voltages.

Potential Impact on Power & Energy Systems: At distribution voltages, the use of solid dielectrics means no more GIS gear, reducing the need for oversight and tracking of SF6. It also means simpler training for installation and maintenance.

K. Smart Transformers

Description: The Smart Transformer (ST) [25][26] is intended to be used as any other power electronics-based transformers, but with added communication and monitoring capability. It would replace conventional distribution transformers, and enable additional ancillary services to the distribution and transmission grids including: grid disturbance rejection; availability of the DC link connection (depending on the architecture adopted); voltage regulation and load consumption shaping capability by means of voltage and frequency control in LV side; voltage support by means of reactive power injection in MV side; AC power flow decoupling between MV and LV grids (if at least one DC stage is present); reduced unit weight and size.

Technologies: Solid State Transformer (SST), Power Electronic Transformer (PET), Distribution Automation Intelligent Universal Transformer (EPRI). The architecture of the ST can vary depending on the grid requirements: ST versions developed so far include a 3-stage solid state transformer solution, where a MV and LV DC link are available; conventional MV/LV transformer in series with a back-to-back converter, enabling the LV DC link without the DC voltage conversion stage; 1-stage AC-AC converter, without DC link and no AC power flow decoupling between MV and LV grids. Power electronics-based on-line tap changers are already present in the market, allowing reduction or elimination of electrical arc switches and increasing dynamic voltage control.

Technologies application: MV/LV substations in weak grids, or in chosen buses where ancillary services can/must be provided; "smart harbor" where vehicles/ships with different frequency systems are connected; wind turbines working with different mechanical speeds; grids with sensitive loads (e.g., data center, hospitals); traction systems (e.g., railway applications).

Technologies benefit: Higher efficiency at partial load vs. conventional transformers; asynchronous connection of the MV and LV grid, enabling independent control of the two grids; enabling DC connection; capability to shape load consumption by means of voltage and frequency control; voltage support in MV grid; data concentrator of LV grid measurements.

Challenges, barriers, gaps: The peak efficiency of STs is lower than in conventional transformers. The main bottleneck is currently the DC/DC converter; its efficiency can be improved with the employment of wide-band semiconductor devices. LV protection system coordination may require redesign, due to the limited overload capability of power electronics and fast dynamic response of the ST controllers (e.g., IGBT blocking control). Higher cost vs. conventional transformer that must be justified by the application-specific need for ST-enabled ancillary grid services.

Status, trend, installations: Advanced experimental stage. Several prototypes have been developed by industry (ABB [27], Alstom, Bombardier, GE, Siemens) and universities (FREEDM center [26], Nottingham University, University of Kiel) for traction and distribution grids applications. Currently, the research field is rapidly growing, concentrating mainly in increasing the system efficiency and reliability, and in developing and refining the ancillary services to be provided in specific applications. Power electronics-based tap changers are already commercially available for specific applications.

Potential impact on Power Energy Systems: An ST increases the control capability of the system and enables new services to the distribution and transmission grids. The asynchronous grid connection offered by STs provides the capability to shape the grid's load consumption. An ST-fed grid thus becomes a controllable resource to an extent. It represents a central data concentrator where the grid measurements are received and analyzed to ensure effective control actions.

L. Transmission & Distribution

Technologies: High-Temperature Superconductor (HTS) power lines; wires of ceramic materials; 2nd generation superconducting wire (DOE's partner SuperPower Inc., 70.5 kA in 322 m HTS wire), composite cores for high-temperature low-sag conductors; parallel distribution sensors; massively deployed sensors for underground cables; satellite imagery for identification of interference with overhead power lines; non-ceramic insulators; microgrid components; advanced algorithms and IEDs; smart sensors; wireless-substation and system-wide communications. Carbon Nanotubes (CNTs).

Technology Name: Carbon Nanotubes (CNT)

Description: CNTs are hollow tubes obtained by rolling a sheet of graphene into a concentric tubular structure. The resulting structure may consist of either single-walled tubes (SWCNTs) or multiple walled tubes (MWCNTs), which are made of multiple concentric layers [28]. CNTs exhibit the property of ballistic conduction, as the mean free path of the electrons is much longer than the dimension of the medium through which they travel [29]. As a result, CNTs have negligible resistance, and are a promising means of reducing power loss for transmission system applications. The use of wires that are doped with chemical additives to raise the Fermi level (the thermodynamic work required to add one electron) would make the CNTs even more conductive. There are additional notable properties that make CNTs especially suitable for power system applications. For example, they are lightweight and flexible, they do not undergo thermal expansion under heavy electrical load, they have low density since they are hollow, and they are practically 100% surface area. This last property is advantageous to the conduction of electricity as electric current flows on the surface of the conductors.

Applications: CNT can be used for underground splices, replacing paper wrapped leads, and other underground splices. They can also be used for conductors, both overhead and underground.

Benefits: Smaller lighter conductors and splices with higher power transmission capability.

Challenges, Barriers, Gaps: Currently the longest CNT are measured in meters not in kilometers. CNT are still very expensive. Long-duration testing in the underground and overhead environments has not been completed, so useful life statistics for CNT are unknown.

Status – Trends, Installations: This is still a laboratory item

Standards Work: Insulated conductor committee, and others will, if this technology emerges from the lab need to update standards for the new materials.

Potential Impact on Power & Energy Systems: CNTs will significantly increase how much power can be pushed through existing conduits. They will reduce splice sizes significantly.

Technology Name: Flexible AC Transmission System (FACTS)

Description: Power quality issues are of critical importance to the consumers of electricity in the industrial, commercial and residential sectors. Currently, there are increasing concerns about the widespread integration of renewable energy sources (RES); deployment of power-electronic-based power systems (e.g. AC/DC/hybrid microgrids); and the widespread use of power-electronics-based loads. The primary power quality issues include harmonics, voltage sags/swells, voltage and frequency fluctuations, and phase imbalances.

In light of the advances in the power semiconductor industry, flexible AC transmission system (FACTS) devices have become a commercially viable solution to mitigate power quality effects in power systems. These devices typically include: static VAR compensator (SVC); static compensator (STATCOM); unified power quality conditioner (UPQC); and dynamic voltage restorer (DVR). The main limitation of FACTS devices is that their physical location must be carefully selected to provide optimal benefits to the electrical network.

Due to their smaller physical sizes, distributed devices can be used to simplify deployment of power quality mitigation equipment and provide compensation closer to where it is needed. Recently, distributed methods for power quality improvement have gained momentum and novel power-electronic-based devices are being developed for deployment as needed throughout the distribution network. These devices include: active filters; distribution static compensator (D-STATCOM); and electric springs. Active filters and D-STATCOMs can be deployed to compensate for local harmonics, voltage sags/swells, and/or imbalances in the distribution network at their point of connection. Electric springs are integrated into "smart" loads to provide voltage stabilization during periods of excess generation by RES. In addition to mitigating power quality issues, electric springs in smart loads enable demand management functionality on the load side. The electric spring smart load consumes any excess generation by RES to maintain acceptable local voltage levels, thus limiting the use of power curtailment techniques.

Microgrid configurations at the distribution level can also provide improvements to power quality.. Power quality can be improved at the microgrid level by coordinating the operation of the microgrid generation, load and energy storage components using a combination of localized and regional controls. This distributed approach to microgrid asset coordination facilitates outage response and contributes to grid resiliency in the event of a disaster.

Applications: The main applications envisaged for the above technologies include: voltage and current harmonic compensation, voltage sags/swells compensation, reactive power compensation, voltage and frequency regulation and/or unbalance compensation.

There are currently only a few different companies marketing FACTS devices. Notably, coordination of distributed devices and microgrid power quality solutions are not yet common, but are the subject of work by various research groups and active demonstration projects.

Benefits: The potential benefits from these select technologies are expected to be significant for future Smart Grids. Power quality issues generally have an impact on: the customers; manufacturers of appliances and equipment; and service suppliers. Among the many benefits, mitigation of power quality issues can increase the life of certain distribution equipment, reduce transmission losses and improve energy efficiency.

Utilities and network operators are in the best position to implement and benefit from distributed power quality devices. Consumers (residential, industrial and commercial) benefit directly from these devices as the power quality of the electrical supply is better managed by the utilities and the network operators.

Challenges, Barriers, Gaps: There is a need for novel power quality mitigation devices to accommodate the increased penetration of solar PV and other variable energy generation resources. However, from the distributed types, only active filters are available commercially to date. Research and development of the other types of distributed technologies is still ongoing Similarly, there are very few commercially available microgrid control implementations which can provide power quality improvement, unless considering a more robust SCADA system. There are still many challenges which arise from wide-scale deployment of distributed power quality devices, including organizational, planning, analytical, and operational integration issues.

Additional incentives must also be provided for the adoption of smart loads by consumers which can both improve power quality and provide demand side management alternatives. As these alternatives emerge, new methods and techniques for integrated management of these distributed resources are required.

Status, Trends, Installations: Efforts today are currently focused in the microgrid control field, where algorithms and novel devices are being proposed to target specific power quality issues and management of distributed resources. In addition, there are ongoing efforts in the development of D-STATCOMs and smart loads based on the use of electrical springs. However, implementations in these areas are so far available primarily in laboratory settings.

Standards Work: IEC 61000 family of standards on Electromagnetic Compatibility (EMC) which consists of six parts each having several sections; IEEE 1159 recommended practice for monitoring electric power quality; IEEE 519 recommended practice and requirements for harmonic control in electric power systems; IEEE P825 guide for development of transactive energy systems; and, IEEE 1547 series of standards for distributed resources interconnected with electric power systems.

Potential Impact on Power Industry: The impact of these devices on future smart grids is expected to be significant, in light of the expected increase in penetrations of RES and other distributed energy resources, increased installation of power-electronic-based loads and deployment of power-electronic-based power systems. Distributed power quality devices and microgrid solutions will enable simpler reconfiguration of future electrical networks. However, coordinated control of transmission and distribution networks must still be performed to maintain acceptable levels of overall system reliability. The use of distributed “smart” devices significantly increases the difficulty of seamlessly integrating all the resources attached to and maintaining situational awareness of systems operating within the distribution grid.

M. Power Systems Instrumentation and Measurement

Technologies: Programmable Josephson Voltage Standards (PJVS) for power measurements, Pulse-driven AC Josephson Voltage Standards (AC JVS) for voltage and power measurements, GPS-Based System-Wide Synchrophasor Measurements, Smart Metering, Home Area Networks, Demand Response, Optical Sensors for AC high-voltage and high-current measurements, High-Accuracy Rogowski Coils.

Descriptions

Programmable Josephson Voltage Standards (PJVS), Pulse-driven AC Josephson Voltage Standards (AC JVS): After being used for quantum-accuracy AC voltage measurements, AC power standards based on Programmable Josephson Voltage Standards (PJVS) are currently under development at the National Measurement Institutes (NMIs) in North America (NIST, NRC) and Europe (PTB, NPL, and other European NMIs as part of iMERA project). This is a new path to providing traceability to international system of units (SI) through the realizations (called national standards) of units which are primarily based on physical laws and fundamental constants. (The SI units serve as the basis of traceability, which is a fundamental concept for unified system of metrology.) It is expected that the uncertainties of PJVS based power measurements of the order 1-2 μW/VA or better are going to be achieved at power system frequencies. Pulse-driven AC Josephson Voltage Standards (AC JVS) may find application in quantum-accuracy power measurements at higher frequencies, and for distorted waveforms.

GPS-Based System-Wide Synchrophasor Measurements: The development of communications and introduction and availability of a standardized time reference over wide geographic area by GPS laid the foundation for the synchrophasor technology. This in turn provided information not previously available that was needed for system-wide monitoring, control and protection of the power system. Although initial synchrophasor technology development can be traced to over two decades ago, commercialization of this technology had to wait for the enabling deployment of Phasor Measurement Units (PMUs), which has started relatively recently. The synchrophasor technology is only now maturing to support large scale applications. Recent large-scale deployment projects emphasize the importance of standards to assure both accuracy and interoperability. Creation of large interconnected networks of PMUs requires thorough testing, as well as integration of monitoring and control subsystems embedded in the power networks. New uses of PMUs are appearing, such as real-time thermal monitoring of multi-area transmission lines for sags (due to transmitted power, ambient temperature, wind, ice, and other weather conditions). Beside the calibration methods defined by the IEEE standard for synchrophasors, new methods for dynamic calibrations of PMUs are currently being developed by the National Institute of Standards and Technology (NIST) in US, with a possibility that other National Measurement Institutes (NMIs) will join the effort. An NMI's role is also to ensure traceability of PMU measurements to SI units.

Smart Metering: Advances in communication technology enabled moves toward deregulation of the electrical power industry and prompted development of smart metering for residential and industrial customers. Automatic Meter Reading (AMR, interpreted in some places as Advanced Meter Reading) and Advanced Metering Infrastructure (AMI) refer to automated collection of data from electricity (also gas and water) metering devices, transferring data to a center for data storage, billing (possibly based on time-of-use etc.), data analysis (e.g. load profiling), monitoring, and other purposes. Two-way communication capability allows meter configuration and re-configuration. Integrating distributed energy resources in the power system requires two-way metering capability available from smart meters. Communication capability allows for interaction with the customer, which enables customer behavior changes based on energy prices, introduces new dynamics in the system, and opens up space for new services. Smart Meters provide an information basis for Home Area Networks and Demand Response. (E.g. see Smart Metering Canada 2008, with more than 1 million smart meters installed in Ontario at the end of 2007.)

Demand Response: incentive-based: load control, interruptible/curtailable rates, demand bidding/buyback programs, emergency demand programs, capacity market programs (CMP), ancillary-services market programs; time-based: time-of-use (TOU), critical-peak pricing (CPP), real-time pricing (RTP). Customer side technologies relate to optional participation in energy conservation, based on measurements performed by smart meters and the communications with smart meters, smart appliances or other loads and distributed energy resources (DER). The goal is promoting energy conservation, reducing energy cost, and active participation of users in the decision making process allowing for "voluntary demand response," as opposed to "involuntary demand response" applied by electric utilities without the knowledge and consent of other power grid users ('*prosumers*' - i.e. consumers that are also producers).

Optical Sensors: Although the introduction of optical sensors for AC high-voltage and high-current measurements (e.g. based on Pockel's and Faraday's effects) started long ago, a system-wide deployment has yet to take place.

High-Accuracy Rogowski Coils: High-Accuracy Rogowski Coils: Long used in various current sensing applications, such as protective relaying, measurements of high-, impulse-, and transient currents, new developments in Rogowski coils, including innovative designs, new materials, machining techniques and two- or three-dimensional printed circuit board structures are emerging as an increasingly accurate tool for high-current measurements at both higher power and higher frequencies. The introduction of the load reduction, temperature compensation, linearization and other error reducing techniques, device coding, parameter retention, digitization of output signals, and communication to local data acquisition systems have contributed to their performance in some cases satisfying and exceeding IEC Class 0.1 requirements for Electronic Current Transformers.

N. Internet of Things (IoT), Edge, and Fog Computing

Technology: Internet of Things (IoT) [43], Edge Computing [44], Fog Computing [45]

Descriptions: All 3 technologies are related to decentralizing cloud computing. Internet of Things (IoT) extends internet connectivity beyond the traditional set of devices (desktops, laptops, and handheld devices) to a range of devices that have historically been "dumb" and not networked. ItoT is comprised of a network of physical objects with internet connectivity that can communicate and interact with one another. IoT devices often monitor and aggregate sensor data. Edge computing pushes application programs, data, and services that have in recent years been consolidated in the cloud out to cloud-edge devices [44]. Fog computing connects the cloud to the edges with a managed infrastructure. This extends cloud functionality to the edge devices. Fog and Edge Computing suppliers often provide power system customers with Quality of Service (QoS) guarantees, network monitoring, and other advanced functionalities, as is common in other industries. Additionally, some Fog-enabled network devices such as Cisco routers have a general-purpose co-processor.

Applications: Power applications are increasingly becoming decentralized, primarily to support distributed renewable generation. Either direct power applications, or "services" that other apps use, e.g. distributed state estimation can be pushed out of the control center and to the edges of the system. Such applications can be dynamically dispatched whenever conditions warrant. Additionally, synchrophasor estimation, phasor data concentrators, alarm processing, distributed state estimation, distributed voltage stability, and distributed power flow management are among many applications whose decentralization may be made more practical by edge and fog technologies [46].
One of the major IoT areas is related to the Smart Grid, from smart home appliances to energy management systems. The IoT in the electric power systems includes Advanced Metering Infrastructure (AMI), SCADA (Supervisory Control and Data Acquisition), Smart Inverters, Smart Loads, and various Intelligent Electronic Devices (IEDs).

Benefits: Fog and edge computing enable significant reductions in network delay by allowing controllers to be much closer to the controlled system, and provide reductions in data traffic between the edges and the core. Router coprocessors can provide intelligent aggregation one network hop up from the edges, for example serving the role of a phasor data concentrator (PDC). Many utility IT infrastructures are unmanaged [47], so the management inherent in Fog computing can help utility IT infrastructures to be more reliable and secure.

Standards Work: IoT, Edge, and Fog are all fairly recent and still immature technologies. However, NIST [48] and the OpenFog Consortium [49] have begun pre-standardization work.

O. Other Emerging Technologies

Electric Vehicle Technologies: Battery Powered Electric Vehicles (BPEV) - Lithium polymer and lithium ion batteries; Hybrid Electric Vehicles (HEV) – gasoline and batteries, on-board generator and plug-in types; Fuel Cell Electric Vehicles (FCEV) – on-board hydrogen or on-board reformer.
Technology Name: Electric Vehicles (EV)
Description: Moving all types of vehicles from fossil fuels to electricity. Transportation accounts for up to 40 percent of energy use in society. To date, electric vehicles account for less than 1% of the vehicles on the road.
Applications: All transportation.
Benefits: Significant reduction in the use of fossil fuels.
Challenges, Barriers, Gaps: Infrastructure, distribution of electricity, billing, charging, safety and other issues exist. Many working groups are tackling these issues.
Trends, Installations: Electric vehicles are commercially available in 2018 for the first time in all classes of vehicles.
Standards Work: EV's will have major impact on many parts of the electric power industry.
Potential Impact on Power & Energy Systems: If EVs take over the road, demand for electricity will double in most countries.

Technology Name: Metal-Organic Frameworks (M-O)
Description: Metal-Organic frameworks are a laboratory breakthrough that offers a wide range of opportunities. Among the first to be defined are replacing current electrolysis equipment for hydrogen, renewable natural gas, and as a new type of photovoltaic (PV) panels.
Applications: Production of hydrogen, renewable natural gas, PV, and other potential applications are emerging.
Benefits: Much higher efficiency in the lab than current commercial equipment.
Challenges, Barriers, Gaps: This is a laboratory technology. Current M-O devices are millimeters in size.
Trends, Installations: A growing community of researchers are working on variations of the basic framework.
Standards Work: To be determined.
Potential Impact on Power & Energy Systems: To be determined, but potentially large impacts when or if this technology emerges from the laboratory.

Electric Ship Technologies [22]-[23]:

- Electric Power Generation (nuclear, fuel cells, advanced generators, solar power and alternative fuels)
- Electric Propulsion Technology (Machines, Drives, Propulsors; advanced induction motor, permanent magnet motor or high temperature superconducting motor)
- Electrical Power Conversion (power electronic converters, increased current densities, IGBTs for up to 6 kV), Distribution (main bus architecture, DC distribution), and Storage
- Control and Automation (weak power grids; high power density electromagnetic actuators to replace hydraulic actuators)
- Power Quality and Impact of Pulsed Power Loads
- Electric Ship System Integration
- Next-Generation Integrated Electric Power Systems (NGIPS)
- Heat transfer and thermal management (discard, reuse and store waste heat; emerging technologies include: thermal electric cooling, spray cooling, microchannel cooling and advanced heat pipes)
- Protection, Reconfiguration, and Survivability
- New simulation tools for complex power systems
- Electrical Ship Standards

Internet- and multimedia-based technologies: These are already established to a significant degree but continuously developing, as applied to electric power systems, e.g. for situational awareness, education [24], etc.

Internet of Things (IoT) is a network of physical objects with internet connectivity that can communicate and interact with one another through web. One of the major IoT areas is related to the Smart Grid, from smart home appliances to energy management systems. The IoT in the electric power systems includes Advanced Metering Infrastructure (AMI), SCADA (Supervisory Control and Data Acquisition), Smart Inverters, Smart Loads, and various Intelligent Electronic Devices (IEDs).

IV. Conclusion

This white paper identified and provided information on a number of emerging technologies related to technical fields of the IEEE Power and Energy (PES) Society. The paper is conceived as a starting point of an evolving document that would track new developments related to emerging technologies of interest to PES.

Acknowledgment

The editors gratefully acknowledge valuable suggestions and information provided by many of their PES, IEEE and non-IEEE colleagues.

References

[1] Wikipedia. Retrieved on 2017-07-10.
[2] IEEE Power & Energy Society, http://www.ieee-pes.org/. Retrieved on 2017-07-10.
[3] Encyclopedia Britannica. Retrieved on 2017-07-10.
[4] Wikipedia. Retrieved on 2017-07-10.
[5] Merriam-Webster's Online Dictionary. Retrieved on 2017-07-10.
[6] Low Impact Hydropower Institute (LIHI), http://lowimpacthydro.org/. Retrieved on 2017-07-10.
[7] Natural Energy Laboratory of Hawaii Authority, http://nelha.hawaii.gov/. Retrieved on 2017-07-10.

[8] National Renewable Energy Laboratory (NREL), http://www.nrel.gov/. Retrieved on 2017-07-10.
[9] US DoE Renewable Energy, https://energy.gov/eere/office-energy-efficiency-renewable-energy. Retrieved on 2017-07-10.
[10] Paul J. Allen, David C. Green "Web Based Energy Information and Control Systems: Case Studies and Applications", CRC Press, 2005.
[11] US National Institute of Standards and Technology (NIST) Smart Grid Wiki, http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/WebHome. Retrieved on 2017-07-10.
[12] NIST Smart Grid Interoperability Panel (SGIP), https://www.nist.gov/programs-projects/smart-grid-national-coordination/smart-grid-interoperability-panel-sgip. Retrieved on 2017-07-10.
[13] NIST SGIP Interoperability Catalog of Standards http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/SGIPCatalogOfStandards#SGIP_Catalog_of_Standards. Retrieved on 2017-07-10.
[14] US Smart Grid Site https://www.smartgrid.gov/. Retrieved on 2017-07-10.
[15] US Smart Grid Information Clearinghouse http://www.sgiclearinghouse.org/. Retrieved on 2017-07-10.
[16] US National Energy Technology Laboratory (NETL) Smart Grid Implementation Strategy (SGIS), https://www.netl.doe.gov/. Retrieved on 2017-07-10.
[17] GridWise Transactive Energy Framework, Ver. 1.0, The GridWise Architecture Council, US DoE, January 2015. http://www.gridwiseac.org/pdfs/te_framework_report_pnnl-22946.pdf. Retrieved on 2017-07-10.
[18] NIST Transactive Energy Modeling and Simulation Challenge for the Smart Grid, https://www.nist.gov/engineering-laboratory/smart-grid/hot-topics/transactive-energy-modeling-and-simulation-challenge. Retrieved on 2017-07-10.
[19] K. Tweed, "Can One Project Redefine Power Delivery?", https://www.greentechmedia.com/articles/read/can-one-demo-project-redefine-power-delivery. Retrieved on 2017-07-10.
[20] Smart Grid Technologies: Enhancing Your Service, https://www.aepohio.com/save/residential/demoproject/. Retrieved on 2017-07-10.
[21] Energy Flexibility Platform and Interface (EF-Pi) http://fpai-ci.sensorlab.tno.nl/builds/fpai-documentation/development/html/. Retrieved on 2017-07-10.
[22] IEEE Electric Ship Technologies Symposium (ESTS 2005), July 25-27 2005 Philadelphia, PA, USA. http://www.ewh.ieee.org/conf/ests05/. Retrieved on 2017-07-10.
[23] IEEE Electric Ship Technologies Symposium (ESTS 2007), May 21-23, 2007 Arlington, Virginia, USA. http://ewh.ieee.org/conf/ests07/index.php. Retrieved on 2017-07-10.
[24] S. P. Carullo and C.O. Nwankpa, "Interconnected Power Systems Laboratory: A Computer Automated Instructional Facility for Power System Experiments," *IEEE Trans. on Power Systems*, Vol. 17, No. 2, May 2002, pp. 215-222.
[25] M. Liserre, G. Buticchi, M. Andresen, G. De Carne, L. F. Costa and Z. X. Zou, "The Smart Transformer: Impact on the Electric Grid and Technology Challenges," in *IEEE Industrial Electronics Magazine*, vol. 10, no. 2, pp. 46-58, June 2016.
[26] X. She, A. Q. Huang and R. Burgos, "Review of Solid-State Transformer Technologies and Their Application in Power Distribution Systems," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 186-198, Sept. 2013.
[27] C. Zhao, D. Dujic, A. Mester, J. K. Steinke, M. Weiss, S. Lewdeni-Schmid, T. Chaudhuri, and P. Stefanutti, \Power electronic traction transformer: Medium voltage prototype," IEEE Transactions on Industrial Electronics, vol. 61, no. 7, pp. 3257-3268, July 2014.
[28] A. W. Orbaek, A. C. Owens, C. C. Crouse, C. L. Pint, R. H. Hauge, A. R. Barron, "Single walled carbon nanotube growth and chirality dependence on catalyst composition", Nanoscale, Vol. 5, No. 20, pp. 9848-9859
[29] B. Q. Wei, R. Vajtai, and P. M. Ajayan, Reliability and current carrying capacity of carbon nanotubes, Appl. Phys. Lett. 79, 2001
[30] E. Amram Bengio, D. Senic, L. W. Taylor, D. E. Tsentalovich, P. Chen, C. L. Holloway, Aydin Babakhani, Christian J. Long, David R. Novotny, J. C. Booth, N. D. Orloff, and M. Pasquali, "High efficiency carbon nanotube thread antennas", Appl. Phys. Lett. 111, 2017
[31] IEEE Technical Report: Impact of Alternate Gases on Existing IEEE standards (internal document to switchgear and substations committee, plan to publish first half of 2018)
[32] CIGRE Technical Brochure 589 "The Impact of the Application of Vacuum
Switchgear at Transmission Voltages", WG A3.27, published 2014
[33] CIGRE Technical Brochure 683 Technical requirements and specifications of state-of-the-art HVDC switching equipment, 2017
[34] CIGRE Technical report 686 "Mitigating the effects of arcs in MV switchgear", 2017
[35] A.Mercier, M. Larcroix, P. Taillefer, "Benefits of controlled switching of medium voltage circuit breakers", CIRED 2015, Paper 0519
[36] Kyoto Protocol to the United Nations Framework Convention on Climate Change (1998) http://unfccc.int/kyoto_protocol/items/2830.php
[37] P. Glaubitz, H.Ito, R. Smeets, D. Dufornet, et all "CIGRE Position Paper on the Application of SF6 in Transmission and Distribution Networks", May 2014
[38] M. Hyrenbach, T. Hintzen, P. Muller, J.Owens, "Alternative gas insulation in MV switchgear" ; CIRED 2015, Paper 0587
[39] Y. Kieffel, F.Biquez, P. Ponchon "Alternative gas to SF6 for use in HV switchgears", CIRED 2015, Paper 0230
[40] C. Franck et all, "Technical requirements and specifications of state-of-the-art HVDC switching equipment", CIGRE Electra paper #292, June 2017
[41]https://www.socalgas.com/smart-energy/renewable-gas/what-is-renewable-natural-gas retrieved 5 August 2018
[42] https://www.ft.com/content/fa755eec-67e3-11e8-b6eb-4acfcfb08c11 retrieved 5 August 2018
[43] Wikipedia. Retrieved on 2018-7-23.
[44] P. Lopez et al. "Edge-centric Computing: Vision and Challenges", ACM SIGCOMM Computer Communication Review, 45(5), October 2015, 37-42.
[45] "Fog vs Edge Computing", Nebbiolo Technologies, https://www.nebbiolo.tech/wp-content/uploads/whitepaper-fog-vs-edge.pdf, retrieved 2018-7-24.
[46] D. Bakken *et al*., "Towards enhanced power grid management via more dynamic and flexible edge computations," in *Proceedings of the 2017 IEEE Fog World Congress (FWC)*, Santa Clara, CA, 2017, pp. 1-8
[47] "NASPI 2014 Survey of Synchrophasor System Networks — Results and Findings", NASPI Technical Report, www.NASPI.org, July 2015. Retrieved on 2018-7-24.
[48] "Fog Computing Conceptual Model", NIST, Special Publication 500-325, March 2018.
[49] "OpenFog Reference Architecture for Fog Computing", February 2017. https://www.openfogconsortium.org. Retrieved 2017-10-15.