Radio Science and Wireless Communications for the Smart Grid

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***Abstract*— The smart grid paradigm is set to revolutionize electrical energy delivery over the next two decades. The advantages will be manifold but the challenges to realization will be correspondingly great and the cost will be large. The probable structure of the smart power grid is reviewed and contrasted with that of the traditional grid. The requirements of the communications component of the smart grid are outlined and the possible roles of wireless communication technologies highlighted. The electromagnetic environment in which smart grid wireless technology will have to operate is discussed as is the application of radio science to insulation condition monitoring and asset management of plant.**

***Index Terms*— Smart grid, communication architecture, wireless, partial discharge, radiometer, condition monitoring, asset management.**

I. INTRODUCTION

The smart grid is a paradigm shifting concept for the delivery of electrical energy. The essence of the paradigm shift is a change from a largely passive, radial, delivery network ‘broadcasting’ energy at a rate instantaneously matched to a set of time-varying, but uncooperative, loads to a predominantly active, meshed, delivery network that routes energy to loads which cooperate in balancing energy supply and demand.

In contrast to a passive network, an active delivery network requires control. The implication is that the smart grid will need orders of magnitude more monitoring and automation than the traditional grid, requiring the incorporation of sensors, control algorithms and actuators on a massively increased scale. Data transmission from sensors to intelligence, and the transmission of control signals from intelligence to actuators, requires a communication system. Intelligence, in this context, includes traditional (deterministic) control loops, artificial intelligence (expert systems, neural networks, fuzzy logic, multi-agent systems etc.) and (human) operator intervention; the latter both to set policy and make high-level operational decisions. Such operator intervention will be at the highest, most demanding, cognitive level and the quality of decisions will depend sensitively on the clarity, objectivity and ergonomic design of the grid-human interface [1]. This aspect of smart grid design will be as important as the quality of the grid automation.)

The requirement for intelligence (information processing) and communications in a smart grid has resulted in it being characterized as the application of ICT to the power network. The smart grid has also been referred to as the convergence of the power and communications networks.

No single, universally accepted, definition of the smart grid has yet emerged. A definition (one of many) is offered here:

> *A smart grid is a generation, transmission, distribution and utilization grid to which sensors, intelligence and actuators have been massively applied realizing a more robust, more efficient, more adaptive, more sustainable and cheaper supply system.*

One, more, or all of the improvements listed in the above definition may derive in whole, or in part, from the active engagement of consumers as energy generating, storage and load-regulating agents; their behaviour in these roles motivated by, and mediated through, appropriate tariff structures.

II. THE TRADITIONAL POWER GRID

The traditional power system comprises:

- Generation
- Transmission
- Distribution
- Loads

Generation is predominantly confined to a (relatively) small number of large, centralized, generating sets. The voltage is stepped up from tens of kilovolts to hundreds of kilovolts for transmission of bulk energy over long distances. The principal characteristics of this long-distance transmission network (apart from its high voltage) are that (i) it has a mesh structure and (ii) the direction of energy transport along any of the interconnecting lines may be in either direction, depending on the geographical distribution of load and the geographical distribution of available, or preferred, plant. (Availability of plant may change, of course, due to faults and maintenance and preferred plant may change in response to changing operating costs.) At the edge of the transmission network the voltage is then stepped down for more local distribution to individual consumers. The principal characteristic of the

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distribution network is its radial, or tree-like, structure; energy flow always being in the same direction away from the transmission network and towards the customer. As the energy flows outwards along the transmission lines it may be stepped down further in voltage. Figure 1 is a schematic diagram of a traditional power network and Figure 2 illustrates its traditional network structure.

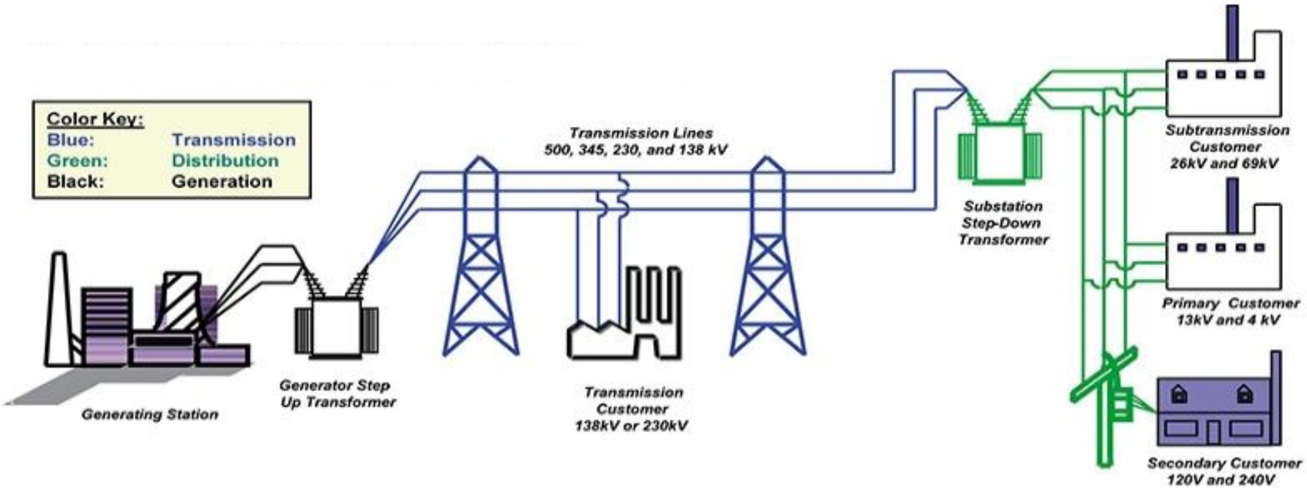

Figure 1. Schematic representation of the traditional grid [2]

If aggregate generation exceeds aggregate demand then the frequency of the system will rise above its nominal value (50 Hz or 60 Hz depending on country). Conversely, if demand exceeds load then system frequency will fall.

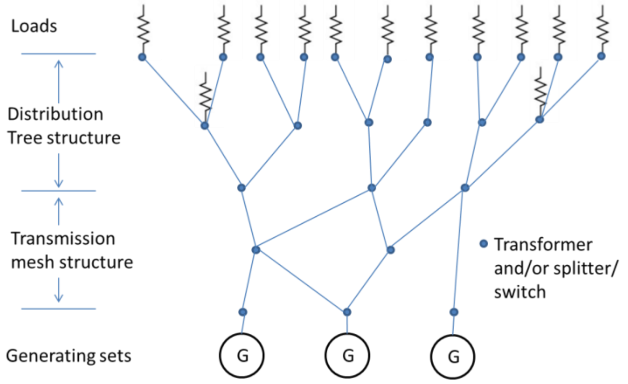

Figure 2. Traditional mesh-tree grid topology

In order to keep the system frequency within statuary limits demand and supply must be matched. The loads in a traditional network take no account of mismatch between energy supply and demand; the supply side of the system taking sole responsibility for balancing these quantities.

III THE SMART POWER GRID

The proliferation of renewable energy sources and micro-generation (much of which is also renewable) embedded at all voltage levels across the grid has been encouraged politically, partly to help governments realize targets for reductions in the emission of CO_2 associated with the burning of fossil fuels. Embedding generation at the periphery of the radial, low-voltage, network means that power flows can be bidirectional even at the network edges. This removes one of the principal distinctions between the transmission and distribution networks. Figure 3 shows the likely structure of the smart grid power network comprising a hierarchy of interconnecting, meshed, nano-, micro- and macrogrids.

The structuring of a grid using interconnected microgrids has some significant advantages. Control can be devolved, for example, such that each microgrid balances, as far as possible, its own (embedded) supply and demand, importing or exporting only the net energy imbalance to its neighbouring microgrids. In this way energy is used as closely as possible to its point of generation, minimizing energy transport and thus minimizing costs (both operational, as reflected in grid losses, and capital, as reflected in the required grid capacity). A further advantage of the ‘grid-of-microgrids’ structure is that islanded operation of microgrids (i.e. the continued operation of a microgrid disconnected from the main grid) is possible in order to maintain supply to consumers should disconnection

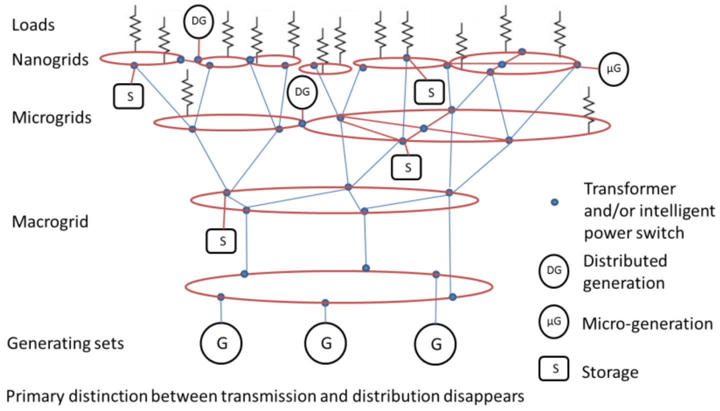

Figure 3. Smart grid ring/mesh structure

from the main grid become necessary.

IV SMART GRID COMMUNICATIONS

A popular model [3, 4] divides the smart grid into the following seven domains:

- Bulk Generation
- Transmission
- Distribution
- Consumers
- Operations
- Service providers
- Markets

Bulk generation refers to traditional generating plant (coal, gas, nuclear, large renewable plants including hydro etc.) with embedded micro-generation being considered part of the distribution system. The smart grid communication system must connect each domain to all other domains via a plethora of different control, automation and decision functions. Each function imposes different requirements and constraints on the associate communications links. Some examples are listed in Table I [5]. The challenge for communications engineers is to provide a reliable communications infrastructure that adequately supports such a large set of disparate requirements at a cost that makes the smart grid economically viable.

A question that was addressed at a recent UK workshop on smart grid communications [6] was whether communications technologies already exist that can address all smart grid communications requirements or not. There appeared to be a consensus (with which the authors agree) that current technologies can address these requirements and that research into new technologies aimed specifically at the smart grid is probably not necessary. [There may have been dissenters; it is the (strong) impression of one of the authors who was present at the workshop that is being reported here.] The view, which is also that of the authors, was that the principal, and urgent, research requirement is a better understanding of how existing technologies can be deployed and integrated to realize the requirements of the smart grid communications network.

There is a temptation to think that the Internet, and its extension to the Internet of Things (IoT), might provide a unifying technology infrastructure that will satisfy all these communications requirements. Whilst the IoT will undoubtedly play an important (conceivably central) role and the smart grid communication system might well look ‘IoT-shaped’, it is unlikely that the IoT, of itself, will be able to meet all smart grid communications requirements. A key issue, in this context, is how quality–of-service (QoS) for the various different functionalities can be guaranteed.

Table I Communication network requirements [5]

Application	Security	Bandwidth	Reliability	Coverge	Latency	Back-up Power
Advanced Metering Infrastructure	High	14-100 kbps per node	99.0-99.99%	20-100 %	2000 ms	0-4 hours
AMI Network Management	High	56-100 kbps	99.00%	20-100%	1000-2000 ms	0-4 hours
Automated Feeder Switching	High	9.6-56 kbps	99.0-99.99%	20-100%	300-2000 ms	8-24 hours
Capacitor Bank Control	Medium	9.6-100 kbps	96.0-99.00%	20-90%	500-2000 ms	0 hours
Charging Plug-In Electric Vehicles	Medium	9.6-56 kbps	99.0-99.90%	20-100%	2000 ms - 5 min.	0 hours
Demand Response	High	56 kbps	99.00%	100%	2000 ms	0 hours
Direct Load Control	High	14-100 kbps per node	99.0-99.99%	20-100 %	2000 ms	0-4 hours
Distributed Generation	High	9.6-56 kbps	99.0-99.99%	90-100%	300-2000 ms	0-1 hour
Distribution Asset Management	High	56 kbps	99.00%	100%	2000 ms	0 hours
Emergency Response	Medium	45-250 kbps	99.99%	95%	500 ms	72 hours
Fault Current Indicator	Medium	9.6 kbps	99.00-99.999%	20-90%	500-2000 ms	0 hours
In-home Displays	High	9.6-56 kbps	99.0-99.99%	20-100%	300 -2000 ms	0-1 hour
Meter Data Management	High	56 kbps	99.00%	100%	2000 ms	0 hours
Network Protection Monitoring	Medium - High	56-100 kbps	99.00-99.999%	100%	2000-5000 ms	0 hours
Outage Management	High	56 kbps	99.00%	100%	2000 ms	0 hours
Price Signaling	Medium	9.6-56 kbps	99.0-99.90%	20-100%	2000 ms - 5 min.	0 hours
Real-time Pricing	High	14-100 kbps per node	99.0-99.99%	20-100 %	2000 ms	0-4 hours
Remote Connect/Disconnect	High	56-100 kbps	99.00%	20-100 %	2000-5000 ms	0 hours
Routine Dispatch	Medium	9.6-64 kbps	99.99%	95%	500 ms	72 hours
Transformer Monitoring	Medium	56 kbps	99.00-99.999%	20-90%	500-2000 ms	0 hours
Voltage and Current Monitoring	Medium	56-100 kbps	99.00-99.999%	100%	2000-5000 ms	0 hours
Workforce Automation	Medium	256-300 kbps	99.90%	90%	500 ms	8 hours

The communications architecture of the smart grid will clearly require a hierarchical structure if it is to be manageable. In the consumer domain this hierarchy includes home area networks (HANs) at the lowest level through neighbourhood area networks (NANs) to a wide area network (WAN). In the distribution domain the equivalent might be wireless sensor networks (WSNs) and local area networks (LANs) through Field area networks (FANs) to a WAN. The authors believe that in order for the communications infrastructure to evolve naturally along with the power system then the communications architecture will need to reflect (at some level) the architecture of the grid-of-microgrids. The difficulty with this is that there are some grid functions (the most obvious example being protection) that have particularly demanding maximum latency requirements but may have to provide connectivity over distances normally associated with a WAN. Passing data packets up (and then down) through a series of hierarchical networks that precisely reflects the grid-of-microgrids is not going to be able to meet all these latency requirements. The communications architecture and associate protocols will require a 'tunnelling' capability, therefore, to support such critical, low-latency, functions.

The smart grid communications infrastructure will incorporate a heterogeneous mix of many existing technologies. Whilst it is not possible to map technologies uniquely to grid domains, or even to specific functions and applications within those domains, some broad, short to medium term, predications can probably be made with reasonable confidence.

In the transmission domain, for example, SDH/SONET and Ethernet or IP over MPLS using fibre (particularly OPGW) seem likely to be important components in a wired core network. (The fibre may be supplemented by microwave links in regions where the installation of fibre is difficult or uneconomic.) In the distribution system ADSS cable and BPL (at MV) and PLC (at LV) may be comparably important.

The last mile (i.e. from a backbone node to the customer premises) is less critical since loss (or delayed) communications in the microgrid prejudices the supply of fewer customers than in the macrogrid. The data-rate requirements are also less demanding at the edge of the network since only modest data aggregation (largely in the context of AMI) will be present within a single microgrid. (This argument may be less true for large commercial and industrial consumers taking supply at a higher voltage; the cost/benefit ratio of providing a particular QoS - in its widest sense including data-rate, reliability, latency limits etc. - being inversely proportional to load.)

Wireless technologies may be particularly appropriate close to, and within, customer premises since the bandwidths will be modest, latency limits will be less demanding and multiple retransmissions of data may be acceptable. Table II compares some of the wireless technologies that might be deployed to realize the AMI segment of the network.

Table II Comparison of candidate NAN and HAN wireless technologies [7]

Scale/ range	Technology	Range (m)	Latency	Reliability	Cost/ Convenience
NAN/ 10s m	WiMAX	30,000	Low	High	Medium/ Medium
	Cellular (e.g. 3G/LTE)	30,000	Low	High	Medium/ Low
	802.22	30,000	Medium	Medium	High/ Medium
HAN/ 100s m	WiFi	200	Medium-High	Low-Medium	Low
	ZigBee	100	Low-Medium	Medium	Low
	Bluetooth	100	Low	Medium	Low

There may be wired competition to the wireless technologies in Table II. Ethernet and PLC, for example, will probably have a significant role in HANs and PLC/BPL may, similarly, have a role in NANs.

V. THE SMART GRID ELECTROMAGNETIC ENVIRONMENT

The environment in which smart grid wireless technologies will have to operate is challenging. Increasing use of power electronics for rectification, inversion and control of power flows generates switching transients that are not only potential sources of power quality degradation but may have energy spectra that extend to sufficiently high frequencies to be radiated. Electromechanical switching operations and fault currents also generate transients that may result in radiation of RF energy. Partial discharge due to damaged, aging or otherwise compromised insulation is also known to radiate significant energy at frequencies up to 100s of MHz and may radiate measurable energy into the GHz region of the spectrum.

The level of electromagnetic interference (EMI), which wireless technologies would be exposed to in smart grid installations is location and time dependent. The IEC 61000-2-5 standard [8] divides the grid infrastructure into three geographical categories: residential, commercial and industrial. Smart grid installations in industrial locations (including substations) require robust wireless receivers which have increased immunity to RF noise from sources such as partial discharges and switching transients. Typical wireless receivers are designed for operation in the presence of Gaussian noise, but the characteristics of the RF noise originating from partial discharges and switching transients is non-Gaussian and impulsive. This motivated a study [9, 10] of substation impulsive noise in order to assess whether conventional wireless technologies are sufficiently robust to operate effectively and reliably in the substation environment. In this study RFI measurements were made using a broadband impulsive noise detection and recording system in a 400/275/132 kV, air-insulated, electricity substation. The impulsive component of the recorded data was extracted using the wavelet packet transform and the best-fit parameters of a symmetric α-stable (SαS) random process were established. Figure 4 shows an example time series of the impulsive noise process generated by the SαS with three different parameters. The physical-layer performance of several wireless technologies operating in the presence of impulsive noise generated using the model were then investigated. Figure 5 shows the simulated performance of a ZigBee receiver. (GSNR in Figure 5 denotes generalized SNR which, for technical reasons, must be used to characterize SNR in the case of SαS processes.) The results (Figure 5 and e.g. [11]) suggest that at least some wireless technologies may be more susceptible to the impulsive noise found in substations than the Gaussian noise for which they are primarily designed. This does not mean that wireless communications technologies are inappropriate for deployment in smart grid applications. The wide-area spatial, and long-term temporal, distribution of impulsive noise in the grid environment not is, as yet, satisfactorily established. (It seems likely that there will be impulsive noise 'hot-spots' close to specific items of plant.) More measurements to characterize the smart grid electromagnetic environment and, assess its practical impact on the performance of candidate wireless technologies, are needed.

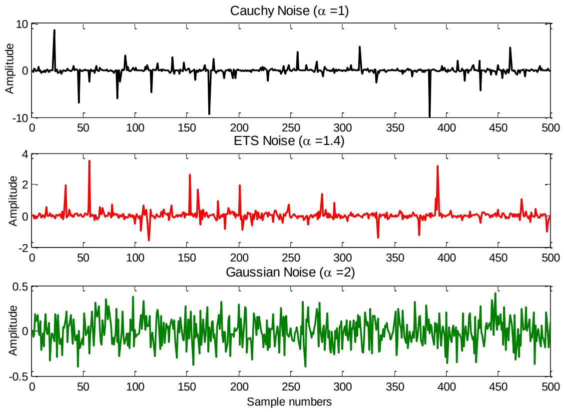

Figure 4 Example SαS impulsive noise processes.

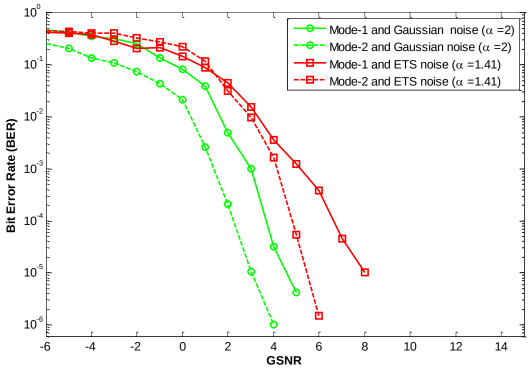

Figure 5 Performance of an IEEE 802.15.4 receiver in the presence of impulsive and Gaussian noise.

VI. INSULATION CONDITION MONITORING

One of the primary characteristics of the smart grid is wide area, real-time, visibility of grid state realized by a wide area monitoring System (WAMS). The usual example of WAMS given in the context of grid operations is the deployment phase measurement units (PMUs), also known as synchrophasors. These are devices attached to a bus that measure and report the amplitudes and phase angles of the bus current and voltage. PMUs have become practical with the advent of GPS and similar technologies. It is undoubtedly the case that the use of synchrophasor data will be one of the primary mechanisms for maintaining the stability of the smart grid.

Of only slightly less importance to optimum grid operation, however, is the wide area visibility of plant health. If the condition of plant can be ubiquitously and continuously monitored then the network can be configured to optimize asset use. Plant at risk of failing, for example, could be disconnected with confidence prior to failure but not prematurely so. Prediction of equipment failure would allow networks to be reconfigured as necessary to minimize CMLs (customer minutes lost) whilst simultaneously minimizing system losses. The replacement of plant could effectively become a just-in-time-operation reducing capital expenditure. A truly self-diagnosing, self-healing smart grid clearly needs to have wide area visibility of plant health.

The impulsive noise radiated by compromised insulation under electrical stress is a potential source of wireless system performance degradation as described in Section V. Since the noise is indicative of insulation degradation, however, it can be used to monitor insulation health. Such monitoring already takes place but is often in the form of an RFI substation survey conducted manually by a technician using a hand-held broadband radio receiver. The experienced technician will walk the substation and find sources of impulsive noise by moving up the gradient of noise intensity (as displayed on a screen or heard via a receiver audio output). The surveys are typically carried out annually or biennially. Unfortunately insulation defects, once established, may degrade rapidly with time and a source of RFI not detected (or deemed inconsequential) during one survey may become a cause of catastrophic plant failure before the next survey.

Work has already been reported describing equipment for the automated location of impulsive noise sources (typically of PD origin) in substations using free standing radio receivers, e.g. [12, 13, 14]. Most such work uses recording of an impulsive noise signal at spatially separated antennas followed by time gating to extract the first segment of the direct line-of-sight (LOS) signal. The LOS signals are then cross correlated to establish their time-difference-of-arrival (TDOA) and the location of the source is found by tri- (or multi-) lateration.

The advantage of using free-standing ('free-space') receivers, rather than PD measurement sensors that attach to individual items of equipment is that deployment (and reconfiguration) is trivial. The free-standing receivers have no physical contact with any item of plant meaning they can be installed retrospectively without taking plant out of service. Furthermore, a modest number of sensors can monitor many items of plant.

A recent proposal to develop a WSN for the ubiquitous and continuous monitoring of insulation health [15] suggests a network of radiometers to measure the signal strength (or received power) of PD radiation and the location of the PD source by path-loss inversion or pattern matching. In both cases the WSN would need to be calibrated by the transmission of emulated PD signals (of known power) from each of the nodes in the WSN.

Figure 6 shows a schematic diagram a hypothetical WSN in a substation compound. The emulated PD transmissions would need to be made from each node in the network in turn. These transmissions could be used to measure the path-loss from each node to all other nodes. A source of genuine PD (distinguished from emulated PD by its lack of well-defined, periodic, transmission slots) can then be located (at least approximately) by path-loss inversion and multi-lateration or by pattern matching to the spatial signatures of emulated PD transmissions.

The use of PD signal amplitude rather TDOA technology to locate PD simplifies the technology considerably and improves scalability.

Figure 6 A WSN comprising free-standing radiometers insulation condition monitoring.

VII. CONCLUSIONS

A brief review of the roles of radio science and wireless communications in the future smart grid has been presented. The features of the smart grid that distinguish it from the traditional grid have been outlined and the role of communication technology has been described. It has been suggested that the principal and most urgent open research questions for smart grid communications relate to the architecture, and interoperability, of a heterogeneous mix of existing communications technologies rather than the invention of new technologies. An architecture is suggested that reflects a grid-of-microgrids structure but with a tunnelling capability to realise the low-latency, wide-area, requirement of some grid functions. The roles of wireless communication, especially in the distribution and consumer segments of the grid have been briefly discussed. The application of free-standing radio receivers to realise wide area visibility of insulation health for the ubiquitous and continuous condition monitoring of plant has been reviewed. A scalable approach to such monitoring using a WSN based on a network of radiometers measuring only PD signal strength has been suggested.

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