1

The Smart Grid

1.1 Introduction

Established electric power systems, which have developed over the past 70 years, feed electrical power from large central generators up through generator transformers to a high voltage interconnected network, known as the transmission grid. Each individual generator unit, whether powered by hydropower, nuclear power or fossil fuelled, is large with a rating of up to 1000 MW. The transmission grid is used to transport the electrical power, sometimes over considerable distances, and this power is then extracted and passed through a series of distribution transformers to final circuits for delivery to the end customers.

The part of the power system supplying energy (the large generating units and the transmission grid) has good communication links to ensure its effective operation, to enable market transactions, to maintain the security of the system, and to facilitate the integrated operation of the generators and the transmission circuits. This part of the power system has some automatic control systems though these may be limited to local, discrete functions to ensure predictable behaviour by the generators and the transmission network during major disturbances.

The distribution system, feeding load, is very extensive but is almost entirely passive with little communication and only limited local controls. Other than for the very largest loads (for example, in a steelworks or in aluminium smelters), there is no real-time monitoring of either the voltage being offered to a load or the current being drawn by it. There is very little interaction between the loads and the power system other than the supply of load energy whenever it is demanded.

The present revolution in communication systems, particularly stimulated by the internet, offers the possibility of much greater monitoring and control throughout the power system and hence more effective, flexible and lower cost operation. The Smart Grid is an opportunity to use new ICTs (Information and Communication Technologies) to revolutionise the electrical power system. However, due to the huge size of the power system and the scale of investment that has been made in it over the years, any significant change will be expensive and requires careful justification.

The consensus among climate scientists is clear that man-made greenhouse gases are leading to dangerous climate change. Hence ways of using energy more effectively and generating electricity without the production of CO_2 must be found. The effective management of loads

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and reduction of losses and wasted energy needs accurate information while the use of large amounts of renewable generation requires the integration of the load in the operation of the power system in order to help balance supply and demand. Smart meters are an important element of the Smart Grid as they can provide information about the loads and hence the power flows throughout the network. Once all the parts of the power system are monitored, its state becomes observable and many possibilities for control emerge.

In the UK, the anticipated future de-carbonised electrical power system is likely to rely on generation from a combination of renewables, nuclear generators and fossil-fuelled plants with carbon capture and storage. This combination of generation is difficult to manage as it consists of variable renewable generation and large nuclear and fossil generators with carbon capture and storage that, for technical and commercial reasons, will run mainly at constant output. It is hard to see how such a power system can be operated cost-effectively without the monitoring and control provided by a Smart Grid.

1.2 Why implement the Smart Grid now?

Since about 2005, there has been increasing interest in the Smart Grid. The recognition that ICT offers significant opportunities to modernise the operation of the electrical networks has coincided with an understanding that the power sector can only be de-carbonised at a realistic cost if it is monitored and controlled effectively. In addition, a number of more detailed reasons have now coincided to stimulate interest in the Smart Grid.

1.2.1 Ageing assets and lack of circuit capacity

In many parts of the world (for example, the USA and most countries in Europe), the power system expanded rapidly from the 1950s and the transmission and distribution equipment that was installed then is now beyond its design life and in need of replacement. The capital costs of like-for-like replacement will be very high and it is even questionable if the required power equipment manufacturing capacity and the skilled staff are now available. The need to refurbish the transmission and distribution circuits is an obvious opportunity to innovate with new designs and operating practices.

In many countries the overhead line circuits, needed to meet load growth or to connect renewable generation, have been delayed for up to 10 years due to difficulties in obtaining rights-of-way and environmental permits. Therefore some of the existing power transmission and distribution lines are operating near their capacity and some renewable generation cannot be connected. This calls for more intelligent methods of increasing the power transfer capacity of circuits dynamically and rerouting the power flows through less loaded circuits.

1.2.2 Thermal constraints

Thermal constraints in existing transmission and distribution lines and equipment are the ultimate limit of their power transfer capability. When power equipment carries current in excess of its thermal rating, it becomes over-heated and its insulation deteriorates rapidly. This leads to a reduction in the life of the equipment and an increasing incidence of faults.

If an overhead line passes too much current, the conductor lengthens, the sag of the catenary increases, and the clearance to the ground is reduced. Any reduction in the clearance of an overhead line to the ground has important consequences both for an increase in the number of faults but also as a danger to public safety. Thermal constraints depend on environmental conditions, that change through the year. Hence the use of dynamic ratings can increase circuit capacity at times.

1.2.3 Operational constraints

Any power system operates within prescribed voltage and frequency limits. If the voltage exceeds its upper limit, the insulation of components of the power system and consumer equipment may be damaged, leading to short-circuit faults. Too low a voltage may cause malfunctions of customer equipment and lead to excess current and tripping of some lines and generators. The capacity of many traditional distribution circuits is limited by the variations in voltage that occur between times of maximum and minimum load and so the circuits are not loaded near to their thermal limits. Although reduced loading of the circuits leads to low losses, it requires greater capital investment.

Since about 1990, there has been a revival of interest in connecting generation to the distribution network. This distributed generation can cause over-voltages at times of light load, thus requiring the coordinated operation of the local generation, on-load tap changers and other equipment used to control voltage in distribution circuits. The frequency of the power system is governed by the second-by-second balance of generation and demand. Any imbalance is reflected as a deviation in the frequency from 50 or 60 Hz or excessive flows in the tie lines between the control regions of very large power systems. System operators maintain the frequency within strict limits and when it varies, response and reserve services are called upon to bring the frequency back within its operating limits [1]. Under emergency conditions some loads are disconnected to maintain the stability of the system.

Renewable energy generation (for example. wind power, solar PV power) has a varying output which cannot be predicted with certainty hours ahead. A large central fossil-fuelled generator may require 6 hours to start up from cold. Some generators on the system (for example, a large nuclear plant) may operate at a constant output for either technical or commercial reasons. Thus maintaining the supply–demand balance and the system frequency within limits becomes difficult. Part-loaded generation ‘spinning reserve’ or energy storage can address this problem but with a consequent increase in cost. Therefore, power system operators increasingly are seeking frequency response and reserve services from the load demand. It is thought that in future the electrification of domestic heating loads (to reduce emissions of CO_2) and electric vehicle charging will lead to a greater capacity of flexible loads. This would help maintain network stability, reduce the requirement for reserve power from part-loaded generators and the need for network reinforcement.

1.2.4 Security of supply

Modern society requires an increasingly reliable electricity supply as more and more critical loads are connected. The traditional approach to improving reliability was to install additional redundant circuits, at considerable capital cost and environmental impact. Other than disconnecting the faulty circuit, no action was required to maintain supply after a fault. A Smart Grid approach is to use intelligent post-fault reconfiguration so that after the (inevitable) faults in the power system, the supplies to customers are maintained but to avoid the expense of multiple circuits that may be only partly loaded for much of their lives. Fewer redundant circuits result in better utilisation of assets but higher electrical losses.

1.2.5 National initiatives

Many national governments are encouraging Smart Grid initiatives as a cost-effective way to modernise their power system infrastructure while enabling the integration of low-carbon energy resources. Development of the Smart Grid is also seen in many countries as an important economic/commercial opportunity to develop new products and services.

1.2.5.1 China

The Chinese government has declared that by 2020 the carbon emission per-unit of GDP will reduce to 40∼45 per cent of that in 2008. Other drivers for developing the Smart Grid in China are the nation's rapid economic growth and the uneven geographical distribution of electricity generation and consumption.

The State Grid Corporation of China (SGCC) has released a medium–long term plan of the development of the Smart Grid. The SGCC interprets the Smart Grid [2] as

> "*a strong and robust electric power system, which is backboned with Ultra High Voltage (UHV) networks; based on the coordinated development of power grids at different voltage levels; supported by information and communication infrastructure; characterised as an automated, and interoperable power system and the integration of electricity, information, and business flows*."

1.2.5.2 The European Union

The SmartGrids Technology Platform of the European Union (EU) has published a vision and strategy for Europe's electricity networks of the future [3]. It states:

> "*It is vital that Europe's electricity networks are able to integrate all low carbon generation technologies as well as to encourage the demand side to play an active part in the supply chain. This must be done by upgrading and evolving the networks efficiently and economically*."

The SmartGrids Technology Platform identified the following important areas as key challenges that impact on the delivery of the EU-mandated targets for the utilisation of renewable energy, efficiency and carbon reductions by 2020 and 2050:

- strengthening the grid, including extending it offshore;
- developing decentralised architectures for system control;
- delivering communications infrastructure;
- enabling an active demand side;
- integrating intermittent generation;

- enhancing the intelligence of generation, demand and the grid;
- capturing the benefits of distributed generation (DG) and storage;
- preparing for electric vehicles.

1.2.5.3 Japan

In 2009, the Japanese government declared that by 2020 carbon emissions from all sectors will be reduced to 75 per cent of those in 1990 or two-thirds of those in 2005. In order to achieve this target, 28 GW and 53 GW of photovoltaic (PV) generations are required to be installed in the power grid by 2020 and 2030. The Ministry of Economy, Trade and Industry (METI) has set up three study committees since 2008 to look into the Smart Grid and related aspects. These committees were active for a one-year period and were looking at the low-carbon power system (2008–2009), the next-generation transmission and distribution network, the Smart Grid in the Japanese context (2009–2010) and regulatory issues of the next-generation transmission and distribution system (2010–2011). The mandate given to these committees was to discuss the following technical and regulatory issues regarding the large penetration of renewable energy, especially PV generation, into the power grid:

- surplus power under light load conditions;
- frequency fluctuations;
- voltage rise on distribution lines;
- priority interconnection, access and dispatching for renewable energy-based generators;
- cost recovery for building the Smart Grid.

Further, a national project called ‘The Field Test Project on Optimal Control Technologies for the Next-Generation Transmission and Distribution System’ was conducted by 26 electric utilities, manufacturing companies and research laboratories in Japan in order to develop the technologies to solve these problems.

Since the Tohoku earthquake on 11 March 2011, the Smart Grid has been attracting much attention for the reconstruction of the damaged districts and the development of a low-carbon society.

1.2.5.4 The UK

The Department of Energy and Climate Change document *Smarter Grids*: *The Opportunity* [4] states that the aim of developing the Smart Grid is to provide flexibility to the current electricity network, thus enabling a cost-effective and secure transition to a low-carbon energy system. The Smart Grid route map [5] recognises a number of critical developments that will drive the UK electrical system towards a low carbon system. These include:

- rapid expansion of intermittent renewables and less flexible nuclear generation in conjunction with the retirement of flexible coal generation;
- electrification of heating and transport;
- penetration of distributed energy resources which include distributed generation, demand response and storage;
- increasing penetration of electric vehicles.

1.2.5.5 The USA

According to Public Law 110–140-DEC. 19, 2007 [6], the United States of America (the USA)

> "*is supporting modernisation of the electricity transmission and distribution networks to maintain a reliable and secure electricity infrastructure that can meet future demand growth and to achieve increased use of digital information and controls technology; dynamic optimisation of grid operations and resources; deployment and integration of distributed resources and generation; development and incorporation of demand response, demand-side resources, and energy-efficient resources; development of 'smart' technologies for metering, communications and status, and distribution automation; integration of 'smart' appliances and consumer devices; deployment and integration of advanced electricity storage and peak-shaving technologies; provisions to consumers of timely information and control options and development of standards for communication and inter-operability.*"

1.3 What is the Smart Grid?

The Smart Grid concept combines a number of technologies, end-user solutions and addresses a number of policy and regulatory drivers. It does not have a single clear definition.

The European Technology Platform [3] defines the Smart Grid as:

> "*A SmartGrid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.*"

According to the US Department of Energy [7]:

> "*A smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources.*"

In *Smarter Grids: The Opportunity* [4], the Smart Grid is defined as:

> "*A smart grid uses sensing, embedded processing and digital communications to enable the electricity grid to be observable (able to be measured and visualised), controllable (able to manipulated and optimised), automated (able to adapt and self-heal), fully integrated (fully interoperable with existing systems and with the capacity to incorporate a diverse set of energy sources).*"

The literature [7–10] suggests the following attributes of the Smart Grid:

1. It enables demand response and demand side management through the integration of smart meters, smart appliances and consumer loads, micro-generation, and electricity storage (electric vehicles) and by providing customers with information related to energy use and prices. It is anticipated that customers will be provided with information and incentives to modify their consumption pattern to overcome some of the constraints in the power system.
2. It accommodates and facilitates all renewable energy sources, distributed generation, residential micro-generation, and storage options, thus reducing the environmental impact

of the whole electricity sector and also provides means of aggregation. It will provide simplified interconnection similar to 'plug-and-play'.

3. It optimises and efficiently operates assets by intelligent operation of the delivery system (rerouting power, working autonomously) and pursuing efficient asset management. This includes utilising asserts depending on what is needed and when it is needed.
4. It assures and improves reliability and the security of supply by being resilient to disturbances, attacks and natural disasters, anticipating and responding to system disturbances (predictive maintenance and self-healing), and strengthening the security of supply through enhanced transfer capabilities.
5. It maintains the power quality of the electricity supply to cater for sensitive equipment that increases with the digital economy.
6. It opens access to the markets through increased transmission paths, aggregated supply and demand response initiatives and ancillary service provisions.

1.4 Early Smart Grid initiatives

1.4.1 Active distribution networks

Figure 1.1 is a schematic of a simple distribution network with distributed generation (DG). There are many characteristics of this network that differ from a typical passive distribution network. First, the power flow is not unidirectional. The direction of power flows and the voltage magnitudes on the network depend on both the demand and the injected generation. Second, the distributed generators give rise to a wide range of fault currents and hence complex protection and coordination settings are required to protect the network. Third, the

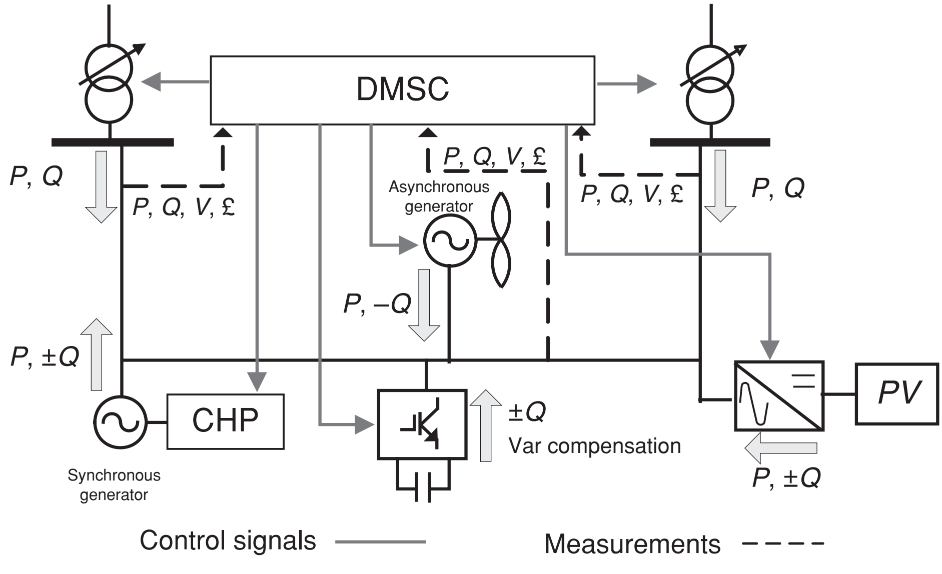

Figure 1.1 Distribution network active management scheme

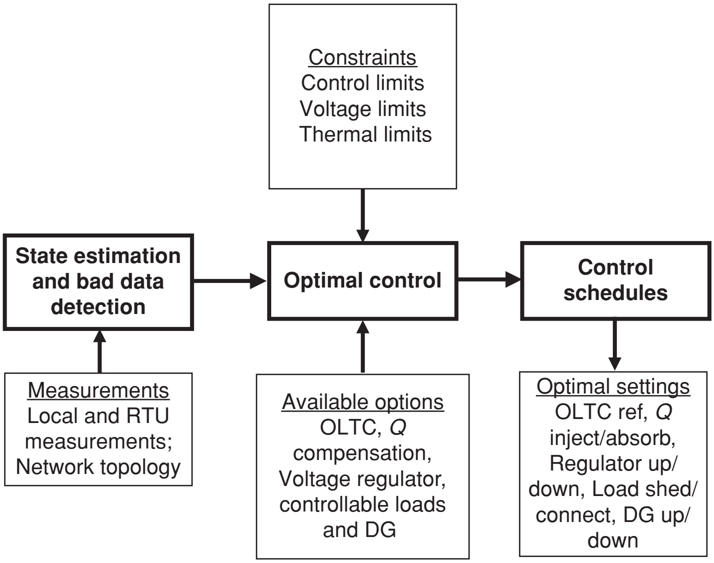

Figure 1.2 Architecture of a DMSC

reactive power flow on the network can be independent of the active power flows. Fourth, many types of DGs are interfaced through power electronics and may inject harmonics into the network.

Figure 1.1 also shows a control scheme suitable for achieving the functions of active control. In this scheme a Distribution Management System Controller (DMSC) assesses the network conditions and takes action to control the network voltages and flows. The DMSC obtains measurements from the network and sends signals to the devices under its control. Control actions may be a transformer tap operation, altering the DG output and injection/absorption of reactive power.

Figure 1.2 shows the DMSC controller building blocks that assess operating conditions and find the control settings for devices connected to the network. The key functions of the DMSC are state estimation, bad data detection and the calculation of optimal control settings.

The DMSC receives a limited number of real-time measurements at set intervals from the network nodes. The measurements are normally voltage, load injections and power flow measurements from the primary substation and other secondary substations. These measurements are used to calculate the network operating conditions. In addition to these real-time measurements, the DMSC uses load models to forecast load injections at each node on the network for a given period that coincides with the real-time measurements. The network topology and impedances are also supplied to the DMSC.

The state estimator (described in Chapter 7) uses this data to assess the network conditions in terms of node voltage magnitudes, line power flows and network injections. Bad measurements coming to the system will be filtered using bad data detection and identification methods.

When the network operating conditions have been assessed, the control algorithm identifies whether the network is operating within its permissible boundaries. This is normally assessed by analysing the network voltage magnitudes at each busbar. The optimisation algorithm is supplied with the available active control options, the limits on these controls and the network operating constraints. Limits on controls are the permissible lower and higher settings of the equipment. Operating constraints are usually voltage limits and thermal ratings of the lines and equipment. The optimal control algorithm calculates the required control settings and optimises the device settings without violating constraints and operating limits.

The solution from the control algorithm is the optimal control schedules that are sent to the devices connected to the network. Such control actions can be single or multiple control actions that would alter the set point of any of the devices by doing any of the following:

- alter the reference of an On-Load Tap Changer (OLTC) transformer/voltage regulator relay;
- request the Automatic Voltage Regulator (AVR) or the governor of a synchronous generator to alter the reactive/active power of the machine;
- send signals to a wind farm Supervisory Control and Data Acquisition (SCADA) system to decrease the wind farm output power;
- shed or connect controllable loads on the network;
- increase or decrease the settings of any reactive power compensation devices;
- reconfigure the network by opening and closing circuit open points.

1.4.2 Virtual power plant

Distributed energy resources (DER) such as micro-generation, distributed generation, electric vehicles and energy storage devices are becoming more numerous due to the many initiatives to de-carbonize the power sector. DERs are too small and too numerous to be treated in a similar way to central generators and are often connected to the network on a ‘connect-and-forget’ basis. The concept of a Virtual Power Plant (VPP) is to aggregate many small generators into blocks that can be controlled by the system operator and then their energy output is traded [11]. Through aggregating the DERs into a portfolio, they become visible to the system operator and can be actively controlled. The aggregated output of the VPP is arranged to have similar technical and commercial characteristics as a central generation unit.

The VPP concept allows individual DERs to gain access to and visibility in the energy markets. Furthermore, system operators can benefit from the optimal use of all the available capacity connected to the network.

The size and technological make-up of a VPP portfolio have a significant effect on the benefits of aggregation seen by its participants. For example, fluctuation of wind generation output can lower the value of the energy sold but variation reduces with increasing geographical distance between the wind farms. If a VPP assembles generation across a range of technologies, the variation of the aggregated output of these generators is likely to reduce.

1.4.3 Other initiatives and demonstrations

1.4.3.1 Galvin electricity initiative

The Galvin vision [12, 13] is an initiative that began in 2005 to define and achieve a ‘perfect power system’. The perfect power system is defined as:

> *“The perfect power system will ensure absolute and universal availability and energy in the quantity and quality necessary to meet every consumer’s needs.”*

The philosophy of a perfect power system differs from the way power systems traditionally have been designed and constructed which assumes a given probability of failure to supply customers, measured by a reliability metric, such as Loss of Load Probability (LOLP). Consideration of LOLP shows that a completely reliable power system can only be provided by using an infinite amount of plant at infinite cost.

Some of the attributes of the perfect power system are similar to those of the Smart Grid. For example, in order to achieve a perfect power system, the power system must meet the following goals:

- be smart, self-sensing, secure, self-correcting and self-healing;
- sustain the failure of individual components without interrupting the service;
- be able to focus on regional, specific area needs;
- be able to meet consumer needs at a reasonable cost with minimum resource utilisation and minimal environmental impact;
- enhance quality of life and improve economic productivity.

The development of the perfect power system is based on integrating devices (smart loads, local generation and storage devices), then buildings (building management systems and micro CHP), followed by construction of an integrated distribution system (shared resources and storage) and finally to set up a fully integrated power system (energy optimisation, market systems and integrated operation).

1.4.3.2 IntelliGrid^{SM}

EPRI's IntelliGrid^{SM} initiative [12, 14], which is creating a technical foundation for the Smart Grid, has a vision of a power system that has the following features:

> - *is made up of numerous automated transmission and distribution systems, all operating in a coordinated, efficient and reliable manner;*
> - *handles emergency conditions with 'self-healing' actions and is responsive to energy-market and utility business enterprise needs;*
> - *serves millions of customers and has an intelligent communications infrastructure enabling the timely, secure and adaptable information flow needed to provide reliable and economic power to the evolving digital economy.*

To realise these attributes, an integrated energy and communication systems architecture should first of all be developed. This will be an open standard-based architecture and technologies such as data networking, communication over a wide variety of physical media and embedded computing will be part of it. This architecture will enable the automated monitoring and control of the power delivery system, increase the capacity of the power delivery system, and enhance the performance and connectivity of the end users.

In addition to the proposed communication architecture, the realisation of the IntelliGrid^{SM} will require enabling technologies such as automation, distributed energy resources, storage, power electronic controllers, market tools, and consumer portals. Automation will become widespread in the electrical generation, consumption and delivery systems. Distributed energy resources and storage devices may offer potential solutions to relieve the necessity to strengthen the power delivery system, to facilitate a range of services to consumers and to provide electricity to customers at lower cost, and with higher security, quality, reliability and availability. Power electronic-based controllers can direct power along specific corridors, increase the power transfer capacity of existing assets, help power quality problems and increase the efficient use of power. Market tools will be developed to facilitate the efficient planning for expansion of the power delivery system, effectively allocating risks, and connecting consumers to markets. The consumer portal contains the smart meter that allows price signals, decisions, communication signals and network intelligent requests to flow seamlessly through the two-way portal.

1.4.3.3 Xcel energy's Smart Grid

Xcel Energy's vision [15] of a smart grid includes

> "*a fully network-connected system that identifies all aspects of the power grid and communicates its status and the impact of consumption decisions (including economic, environmental and reliability impacts) to automated decision-making systems on that network*."

Xcel Energy's Smart Grid implementation involved the development of a number of quick-hit projects. Even though some of these projects were not fully realised, they are listed below as they illustrate different Smart Grid technologies that could be used to build intelligence into the power grid:

1. *Wind Power Storage*: A 1 MW battery energy storage system to demonstrate long-term emission reductions and help to reduce impacts of wind variability.
2. *Neural Networks*: A state-of-the-art system that helps reduce coal slagging and fouling (build-up of hard minerals) of a boiler.
3. *Smart Substation*: Substation automation with new technologies for remote monitoring and then developing an analytics engine that processes data for near real-time decision-making and automated actions.
4. *Smart Distribution Assets*: A system that detects outages and restores them using advanced meter technology.
5. *Smart Outage Management*: Diagnostic software that uses statistics to predict problems in the power distribution system.
6. *Plug-in Hybrid Electric Vehicles*: Investigating vehicle-to-grid technology through field trials.
7. *Consumer Web Portal*: This portal allows customers to program or pre-set their own energy use and automatically control their power consumption based on personal preferences including both energy costs and environmental factors.

1.4.3.4 SCE's Smart Grid

Southern California Edison (SCE)'s Smart Grid strategy encompasses five strategic themes namely, renewable and distributed energy resources integration, grid control and asset optimisation, workforce effectiveness, smart metering, and energy-smart customer solutions [16]. SCE anticipates that these themes will address a broad set of business requirements to better position them to meet current and future power delivery challenges. By 2020, SCE will have 10 million intelligent devices such as smart meters, energy-smart appliances and customer devices, electric vehicles, DERs, inverters and storage technologies that are linked to the grid, providing sensing information and automatically responding to prices/event signals.

SCE has initiated a smart meter connection programme where 5 million meters will be deployed from 2009 to 2012. The main objectives of this programme include adding value through information, and initiating new customer partnerships. The services and information they are going to provide include interval billing, tiered rates and rates based on time of use.

1.5 Overview of the technologies required for the Smart Grid

To fulfil the different requirements of the Smart Grid, the following enabling technologies must be developed and implemented:

1. *Information and communications technologies*: These include:
    (a) two-way communication technologies to provide connectivity between different components in the power system and loads;
    (b) open architectures for plug-and-play of home appliances; electric vehicles and microgeneration;
    (c) communications, and the necessary software and hardware to provide customers with greater information, enable customers to trade in energy markets and enable customers to provide demand-side response;
    (d) software to ensure and maintain the security of information and standards to provide scalability and interoperability of information and communication systems.

    These topics are discussed in Chapters 2–4 of this book.
2. *Sensing, measurement, control and automation technologies*: These include:
    (a) Intelligent Electronic Devices (IED) to provide advanced protective relaying, measurements, fault records and event records for the power system;
    (b) Phasor Measurement Units (PMU) and Wide Area Monitoring, Protection and Control (WAMPAC) to ensure the security of the power system;
    (c) integrated sensors, measurements, control and automation systems and information and communication technologies to provide rapid diagnosis and timely response to any event in different parts of the power system. These will support enhanced asset management and efficient operation of power system components, to help relieve congestion in transmission and distribution circuits and to prevent or minimise potential outages and enable working autonomously when conditions require quick resolution.
    (d) smart appliances, communication, controls and monitors to maximise safety, comfort, convenience, and energy savings of homes;
    (e) smart meters, communication, displays and associated software to allow customers to have greater choice and control over electricity and gas use. They will provide consumers with accurate bills, along with faster and easier supplier switching, to give consumers accurate real-time information on their electricity and gas use and other related information and to enable demand management and demand side participation.

    These topics are discussed in Chapters 5–8.

Table 1.1 Application matrix of different technologies

Application area	Requirement	Information and communications technologies	Sensors, control and automation	Power electronics and energy storage
Industries, homes	Plug-and-play of smart home appliances, electric vehicles, microgeneration	●	●	
	Enabling customers to trade in energy markets	●	●	
	Allowing customers to have greater choice and control over electricity use	●	●	
	Providing consumers with accurate bills, along with faster and easier supplier switching	●	●	
	Giving consumers accurate real-time information on their electricity use and other related information	●	●	
	Enabling integrated management of appliances, electric vehicles (charging and energy storage) and microgeneration	●	●	●
	Enabling demand management and demand side participation	●	●	
Transmission and distribution	Enabling rapid diagnosis and timely response to any event on different part of the power system	●	●	
	Supporting enhanced asset management	●	●	
	Helping relieve congestion in transmission and distribution circuits and preventing or minimising potential outages	●	●	●
Generation	Supporting system operation by controlling renewable energy sources	●	●	●
	Enabling long-distance transport and integration of renewable energy sources			●
	Providing efficient connection of renewable energy sources			●
	Enabling integration and operation of virtual power plants	●	●	●
Power system as a whole	Providing greater flexibility, reliability and quality of the power supply system	●	●	●
	Balancing generation and demand in real time	●	●	●
	Supporting efficient operation of power system components	●	●	●

3. *Power electronics and energy storage*: These include:
   - (a) High Voltage DC (HVDC) transmission and back-to-back schemes and Flexible AC Transmission Systems (FACTS) to enable long distance transport and integration of renewable energy sources;
   - (b) different power electronic interfaces and power electronic supporting devices to provide efficient connection of renewable energy sources and energy storage devices;
   - (c) series capacitors, Unified Power Flow Controllers (UPFC) and other FACTS devices to provide greater control over power flows in the AC grid;
   - (d) HVDC, FACTS and active filters together with integrated communication and control to ensure greater system flexibility, supply reliability and power quality;
   - (e) power electronic interfaces and integrated communication and control to support system operations by controlling renewable energy sources, energy storage and consumer loads;
   - (f) energy storage to facilitate greater flexibility and reliability of the power system.

These topics are discussed in Chapters 9–12 of this book.

Table 1.1 shows the application matrix of different technologies.

References

[1] Erinmez, I.A., Bickers, D.O., Wood, G.F. and Hung, W.W. (1999) *NGC Experience with frequency control in England and Wales: provision of frequency response by generator*. IEEE PES Winter Meeting, 31 January–4 February 1999, New York, USA.

[2] Sun, Q., Wu, J., Zhang, Y. *et al.* (2010) *Comparison of the development of Smart Grids in China and the United Kingdom*. IEEE PES Conference on Innovative Smart Grid Technologies Europe, 11–13 October 2010, Gothenburg, Sweden.

[3] European Commission (2006) *European SmartGrids Technology Platform:Vision and Strategy for Europe's Electricity*, http://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf (accessed on 4 August 2011).

[4] Department of Energy and Climate Change, UK, *Smarter Grids: The Opportunity*, December 2009, http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/futureelectricitynetworks/1_20091203163757_e_@@_smartergridsopportunity.pdf (accessed on 4 August 2011).

[5] Electricity Networks Strategy Group, *A Smart Grid Routemap*, February 2010, http://www.ensg.gov.uk/assets/ensg_routemap_final.pdf (accessed on 4 August 2011).

[6] Kaplan, S.M., Sissine, F., Abel, A. *et al.* (2009) *Smart Grid: Government Series*, The Capitol Net, Virginia.

[7] U.S. Department of Energy, *Smart Grid System Report*, July 2009, http://www.oe.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/SGSRMain_090707_lowres.pdf (accessed on 4 August 2011).

[8] *A Compendium of Modern Grid Technologies*, July 2009, http://www.netl.doe.gov/smartgrid/referenceshelf/whitepapers/Compendium_of_Technologies_APPROVED_2009_08_18.pdf (accessed on 4 August 2011).

[9] European Commission, *ICT for a Low Carbon Economy: Smart Electricity Distribution Networks*, July 2009, http://ec.europa.eu/information_society/activities/

sustainable_growth/docs/sb_publications/pub_smart_edn_web.pdf (accessed on 4 August 2011)

[10] World Economic Forum (2009) *Accelerating Smart Grid Investments*, http://www.weforum.org/pdf/SlimCity/SmartGrid2009.pdf (accessed on 4 August 2011).

[11] Pudjianto, D., Ramsay, C. and Strbac, G. (2007) Virtual power plant and system integration of distributed energy resources. *Renewable Power Generation, IET*, **1** (1), 10–16.

[12] Gellings, C.W. (2009) *The Smart Grid: Enabling Energy Efficiency and Demand Response*, The Fairmont Press, Lilburn.

[13] Galvin, R., Yeager, K. and Stuller, J. (2009) *Perfect Power: How the Microgrid Revolution Will Unleash Cleaner, Greener, More Abundant Energy*, McGraw-Hill, New York.

[14] *The Integrated Energy and Communication Systems Architecture*, 2004, http://www.epri-intelligrid.com/intelligrid/docs/IECSA_VolumeI.pdf (accessed on 4 August 2011).

[15] *XCel Energy Smart Grid: A White Paper*, March 2007, http://smartgridcity.xcelenergy.com/media/pdf/SmartGridWhitePaper.pdf (accessed on 4 August 2011).

[16] *Southern California Edison Smart Grid Strategy and Roadmap*, 2007, http://asset.sce.com/Documents/Environment%20-%20Smart%20Grid/100712_SCE_SmartGridStrategyandRoadmap.pdf (accessed on 4 August 2011).