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SMART GRID

TECHNOLOGY AND APPLICATIONS

WILEY

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WILEY
A John Wiley & Sons, Ltd., Publication

This edition first published 2012

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data

Smart grid : technology and applications / Janaka Ekanayake . . . [et al.].
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-97409-4 (cloth)
1. Smart power grids. I. Ekanayake, J. B. (Janaka B.)
TK3105.S677 2012
621.31–dc23

2011044006

A catalogue record for this book is available from the British Library.

Print ISBN: 978-0-470-97409-4

Typeset in 10/12pt Times by Aptara Inc., New Delhi, India.

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Preface

Electric power systems throughout the world are facing radical change stimulated by the pressing need to decarbonise electricity supply, to replace ageing assets and to make effective use of rapidly developing information and communication technologies (ICTs). These aims all converge in the Smart Grid. The Smart Grid uses advanced information and communication to control this new energy system reliably and efficiently. Some ICT infrastructure already exists for transmission voltages but at present there is very little real-time communication either to or from the customer or in distribution circuits.

The Smart Grid vision is to give much greater visibility to lower voltage networks and to enable the participation of customers in the operation of the power system, particularly through Smart Meters and Smart Homes. The Smart Grid will support improved energy efficiency and allow a much greater utilisation of renewables. Smart Grid research and development is currently well funded in the USA, the UK, China, Japan and the EU. It is an important research topic in all parts of the world and the source of considerable commercial interest.

The aim of the book is to provide a basic discussion of the Smart Grid concept and then, in some detail, to describe the technologies that are required for its realisation. Although the Smart Grid concept is not yet fully defined, the book will be valuable in describing the key enabling technologies and thus permitting the reader to engage with the immediate development of the power system and take part in the debate over the future of the Smart Grid.

This book is the outcome of the authors' experience in teaching to undergraduate and MSc students in China, Japan, Sri Lanka, the UK and the USA and in carrying out research. The content of the book is grouped into three main technologies:

1. Part I Information and communication systems (Chapters 2–4)
2. Part II Sensing, measurement, control and automation (Chapters 5–8)
3. Part III Power electronics and energy storage (Chapters 9–12).

These three groups of technologies are presented in three Parts in this book and are relatively independent of each other. For a course module on an MEng or MSc in power systems or energy Chapters 2-4, 5-7 and 9-11 are likely to be most relevant, whereas for a more general module on the Smart Grid, Chapters 2–5 and Chapters 9 and 12 are likely to be most appropriate.

The technical content of the book includes specialised topics that will appeal to engineers from various disciplines looking to enhance their knowledge of technologies that are making an increasing contribution to the realisation of the Smart Grid.

Acknowledgements

We would like to acknowledge contributions from colleagues and individuals without whom this project will not be a success. Particular thanks are due to Toshiba, S&C Electric Europe Ltd., Tokyo Electric Power Co., Japan Wind and Tianda Qiushi Power New Technology Co. Ltd. for generously making available a number of photographs. Also we would like to thank John Lacari for checking the numerical examples; Jun Liang, Lee Thomas, Alasdair Burchill, Panagiotis Papadopoulos, Carlos Ugalde-Loo and Iñaki Grau for providing information for Chapters 5, 11 and 12; Mahesh Sooriyabandara for checking some chapters; and Luke Livermore, Kamal Samarakoon, Yan He, Sugath Jayasinghe and Bieshoy Awad who helped in numerous ways.

List of Abbreviations

2-D	2-dimensional
3-D	3-dimensional
3G	3rd Generation mobile systems
3GPP	3rd Generation Partnership Project
ACL	Asynchronous Connectionless Link
ADC	Analogue to Digital Conversion or Converter
ADMD	After Diversity Maximum Demand
ADSL	Asymmetric Digital Subscriber Line
ADSS	All-Dielectric Self-Supporting
AES	Advanced Encryption Standard
AGC	Automatic Generation Control
AM	Automated Mapping
AMM	Automatic Meter Management
AMR	Automatic Meter Reading
ARIMA	Autoregressive Integrated Moving Average
ARIMAX	Autoregressive Integrated Moving Average with exogenous variables
ARMA	Autoregressive Moving Average
ARMAX	Autoregressive Moving Average with exogenous variables
ARPANET	Advanced Research Projects Agency Network
ASDs	Adjustable Speed Drives
ASK	Amplitude Shift Keying
AVC	Automatic Voltage Control
BES	Battery Energy Storage
BEV	Battery Electric Vehicles
BPL	Broadband over Power Line
CB	Circuit Breaker
CC	Constant Current
CI	Customer Interruptions
CIM	Common Information Model
CIS	Customer Information System
CML	Customer Minutes Lost
COSEM	Companion Specification for Energy Metering
CSC	Current Source Converter
CSC-HVDC	Current Source Converter High Voltage DC

CSMA/CD	Carrier Sense Multiple Access/Collision Detect
CT	Current Transformer
CTI	Computer Telephony Integration
CV	Constant Voltage
CVT	Capacitor Voltage Transformers
DAC	Digital to Analogue Converter
DARPA	Defense Advanced Research Project Agency
DB	Demand Bidding
DCC	Diode-Clamped Converter
DER	Distributed Energy Resources
DES	Data Encryption Standard
DFIG	Doubly Fed Induction Generators
DG	Distributed Generation
DLC	Direct Load Control
DMS	Distribution Management System
DMSC	Distribution Management System Controller
DNO	Distribution Network Operators
DNS	Domain Name Server
DR	Demand Response
DSB	Demand-Side Bidding
DSI	Demand-Side Integration
DSL	Digital Subscriber Lines
DSM	Demand-Side Management
DSP	Digital Signal Processor
DSR	Demand-Side Response
DVR	Dynamic Voltage Restorer
EDGE	Enhanced Data Rates for GSM Evolution
EMI	Electromagnetic Interference
EMS	Energy Management System
ESS	Extended Service Set
EU	European Union
EV	Electric Vehicles
FACTS	Flexible AC Transmission Systems
FCL	Fault Current Limiters
FCS	Frame Check Sequence
FFD	Full Function Device
FM	Facilities Management
FPC	Full Power Converter
FSIG	Fixed Speed Induction Generator
FSK	Frequency Shift Keying
FTP	File Transfer Protocol
GEO	Geostationary Orbit
GGSN	Gateway GPRS Support Node
GIS	Gas Insulated Substations
GIS	Geographic Information System
GPRS	General Packet Radio Service

GPS	Global Positioning System
GSM	Global System for Mobile Communications
GTO	Gate Turn-off (Thyristor)
HAN	Home-Area Network
HDLC	High-Level Data Link Control
HMI	Human Machine Interface
HTTP	Hypertext Transfer Protocol
HVAC	Heating, Ventilation, Air Conditioning
HVDC	High Voltage DC
ICT	Information and Communication Technology
IED	Intelligent Electronic Device
IGBT	Insulated Gate Bipolar Transistor
IGCT	Insulated Gate Commutated Thyristor
IP	Internet Protocol
IPFC	Interline Power Flow Controller
IPng	IP Next Generation
IPsec	Internet Protocol Security
ITE	Information Technology Equipment
KDC	Key Distribution Centre
LAN	Local Area Network
LCD	Liquid Crystal Displays
LED	Light Emitting Diodes
LLC	Logical Link Control
LMU	Line Matching Unit
LOLP	Loss of Load Probability
M2C	Multi-Modular Converter
MAS	Multi Agent System
MD	Message Digest
MDM	Metre Data Management system
METI	Ministry of Economy, Trade and Industry
MGCC	MicroGrid Central Controllers
MMS	Manufacturing Message Specification
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPLS	Multi Protocol Label Switching
MPPT	Maximum Power Point Tracking
MSB	Most Significant Bit
MTSO	Mobile Telephone Switching Office
NAN	Neighbourhood Area Network
NERC CIP	North America Electric Reliability Corporation – Critical Infrastructure Protection
NOP	Normally Open Point
NPC	Neutral-Point-Clamped
OCGT	Open Cycle Gas Turbines
OFDM	Orthogonal Frequency Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLTCs	On-Load Tap Changers

OMS	Outage Management System
OPGW	OPtical Ground Wires
PCM	Pulse Code Modulation
PDC	Phasor Data Concentrator
PET	Polyethylene Terephathalate
PGA	Programmable Gain Amplifier
PHEV	Plug-in Hybrid Electric Vehicles
PLC	Power Line Carrier
PLL	Phase Locked Loop
PMU	Phasor Measurement Units
PSK	Phase Shift Keying
PSS	Power System Stabilisers
PSTN	Public Switched Telephone Network
PV	Photovoltaic
PWM	Pulse Width Modulation
RFD	Reduced Function Device
RMU	Ring Main Unit
RTU	Remote Terminal Unit
SAP	Session Announcement Protocol
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
SCO	Synchronous Connection Orientated
SGCC	State Grid Corporation of China
SGSN	Serving GPRS Support Node
SHA	Secure Hash Algorithm
SMES	Superconducting Magnetic Energy Storage
SMTP	Simple Mail Transfer Protocol
SNR	Signal to Noise Ratio
SOC	State Of Charge
SVC	Static Var Compensator
TCP	Transmission Control Protocol
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Capacitor
THD	Total Harmonic Distortion
TSC	Thyristor Switched Capacitor
TSSC	Thyristor Switched Series Capacitor
UHV	Ultra High Voltage
UML	Unified Modelling Language
UPFC	Unified Power Flow Controller
UPS	Uninterruptable Power Supplies
URL	Uniform Resource Locator
UTP	Unshielded Twisted Pair
VPN	Virtual Private Network
VPP	Virtual Power Plant
VSC	Voltage Source Converter
VSC-ES	Voltage Source Converters with Energy Storage

VSC-HVDC	Voltage Source Converter HVDC
VT	Voltage Transformer
WAMPAC	Wide Area Monitoring, Protection and Control
WAMSs	Wide-Area Measurement Systems
WAN	Wide Area Network
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless LAN
WLAV	Weighted Least Absolute Value
WLS	Weighted Least Square
WPAN	Wireless Public Area Networks
XOR	Exclusive OR

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