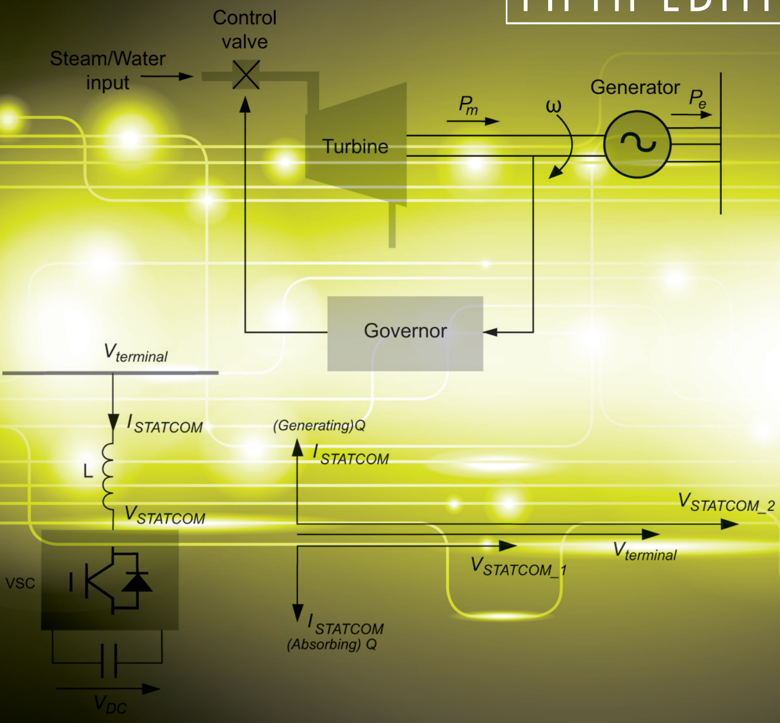
Electric Power Systems

FIFTH EDITION



B.M. WEEDY | B.J. CORY
N. JENKINS | J.B. EKANAYAKE | G. STRBAC

WILEY

Electric Power Systems

Electric Power Systems

Fifth Edition

B.M. Weedy, *University of Southampton, UK*
B.J. Cory, *Imperial College London, UK*
N. Jenkins, *Cardiff University, UK*
J.B. Ekanayake, *Cardiff University, UK*
G. Strbac, *Imperial College London, UK*

WILEY
A John Wiley & Sons, Ltd., Publication

This edition first published 2012
© 2012, John Wiley & Sons Ltd

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

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloging-in-Publication Data

Electric power systems / Brian M. Weedy [...et al.]. – 5th ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-68268-5 (cloth)
1. Electric power systems–Textbooks. 2. Electric power transmission–Textbooks. I. Weedy, Brian M.
TK1001.E4235 2012
621.319′1–dc23
2012010322

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

Print ISBN: 9780470682685

Set in 10/12.5pt, Palatino-Roman by Thomson Digital, Noida, India

Contents

Preface to First Edition

In writing this book the author has been primarily concerned with the presentation of the basic essentials of power-system operation and analysis to students in the final year of first degree courses at universities and colleges of technology. The emphasis is on the consideration of the system as a whole rather than on the engineering details of its constituents, and the treatment presented is aimed at practical conditions and situations rather than theoretical nicety.

In recent years the contents of many undergraduate courses in electrical engineering have become more fundamental in nature with greater emphasis on electromagnetism, network analysis, and control theory. Students with this background will be familiar with much of the work on network theory and the inductance, capacitance, and resistance of lines and cables, which has in the past occupied large parts of textbooks on power supply. In this book these matters have been largely omitted, resulting in what is hoped is a concise account of the operation and analysis of electric power systems. It is the author's intention to present the power system as a system of interconnected elements which may be represented by models, either mathematically or by equivalent electrical circuits. The simplest models will be used consistently with acceptable accuracy and it is hoped that this will result in the wood being seen as well as the trees. In an introductory text such as this no apology is made for the absence of sophisticated models of plant (synchronous machines in particular) and involved mathematical treatments as these are well catered for in more advanced texts to which reference is made.

The book is divided into four main parts, as follows:

a. Introduction, including the establishment of equivalent circuits of the components of the system, the performance of which, when interconnected, forms the main theme.
b. Operation, the manner in which the system is operated and controlled to give secure and economic power supplies.
c. Analysis, the calculation of voltage, power, and reactive power in the system under normal and abnormal conditions. The use of computers is emphasised when dealing with large networks.

d. Limitations of transmittable power owing to the stability of the synchronous machine, voltage stability of loads, and the temperature rises of plant.

It is hoped that the final chapter will form a useful introduction to direct current transmission which promises to play a more and more important role in electricity supply.

The author would like to express his thanks to colleagues and friends for their helpful criticism and advice. To Mr J.P. Perkins for reading the complete draft, to Mr B.A. Carre on digital methods for load flow analysis, and to Mr A.M. Parker on direct current transmission. Finally, thanks are due to past students who for over several years have freely expressed their difficulties in this subject.

Birron M. Weedy
Southampton, 1967

Preface to Fourth Edition

As a university teacher for 40 years, I have always admired the way that Dr Birron Weedy's book has stood out from the numerous texts on the analysis and modelling of power systems, with its emphasis on practical systems rather than extensive theory or mathematics. Over the three previous editions and one revision, the text has been continually updated and honed to provide the essentials of electrical power systems sufficient not only for the final year of a first degree course, but also as a firm foundation for further study. As with all technology, progress produces new devices and understanding requiring revision and updating if a book is to be of continuing value to budding engineers. With power systems, there is another dimension in that changes in social climate and political thinking alter the way they are designed and operated, requiring consideration and understanding of new forms of infrastructure, pricing principles and service provision. Hence the need for an introduction to basic economics and market structures for electricity supply, which is given in a completely new Chapter 12.

In this edition, 10 years on from the last, a rewrite of Chapter 1 has brought in full consideration of CCGT plant, some new possibilities for energy storage, the latest thinking on electromagnetic fields and human health, and loss factor calculations. The major addition to system components and operation has been Flexible a.c. Transmission (FACT) devices using the latest semiconductor power switches and leading to better control of power and var flows. The use of optimisation techniques has been brought into Chapter 6 with powerflow calculations but the increasing availability and use of commercial packages has meant that detailed code writing is no longer quite so important. For stability (Chapter 8), it has been necessary to consider voltage collapse as a separate phenomenon requiring further research into modelling of loads at voltages below 95% or so of nominal. Increasingly, large systems require fast stability assessment through energy-like functions as explained in additions made to this chapter. Static-shunt variable compensators have been included in Chapter 9 with a revised look at h.v.d.c. transmission. Many d.c. schemes now exist around the world and are continually being added to so the description of an example scheme has been omitted. Chapter 11 now includes many new sections with updates on switchgear, and comprehensive introductions to digital (numerical) protection principles, monitoring and control with SCADA, state estimation, and the concept of Energy Management Systems (EMS) for system operation.

Readers who have been brought up on previous editions of this work will realise that detailed design of overhead and underground systems and components has been omitted from this edition. Fortunately, adequate textbooks on these topics are available, including an excellent book by Dr Weedy, and reference to these texts is recommended for detailed study if the principles given in Chapter 3 herein are insufficient. Many other texts (including some 'advanced' ones) are listed in a new organisation of the bibliography, together with a chapter-referencing key which I hope will enable the reader to quickly determine the appropriate texts to look up. In addition, mainly for historical purposes, a list of significant or 'milestone' papers and articles is provided for the interested student.

Finally, it has been an honour to be asked to update such a well-known book and I hope that it still retains much of the practical flavour pioneered by Dr Weedy. I am particularly indebted to my colleagues, Dr Donald Macdonald (for much help with a rewrite of the material about electrical generators) and Dr Alun Coonick for his prompting regarding the inclusion of new concepts. My thanks also go to the various reviewers of the previous editions for their helpful suggestions and comments which I have tried to include in this new edition. Any errors and omissions are entirely my responsibility and I look forward to receiving feedback from students and lecturers alike.

Brian J. Cory
Imperial College, London, 1998

Publisher's Note

Dr B. M. Weedy died in December 1997 during the production of this fourth edition.

Preface to Fifth Edition

We were delighted to be asked to revise this classic textbook. From the earlier editions we had gained much, both as undergraduate students and throughout our careers. Both Dr Weedy and Dr Cory can only be described as giants of power system education and the breadth of their vision and clarity of thought is evident throughout the text. Reading it carefully, for the purposes of revision, was a most rewarding experience and even after many years studying and teaching power systems we found new insights on almost every page.

We have attempted to stay true to the style and structure of the book while adding up-to-date material and including examples of computer based simulation. We were conscious that this book is intended to support a 3rd or 4th year undergraduate course and it is too easy when revising a book to continue to add material and so obscure rather than illuminate the fundamental principles. This we have attempted not to do. Chapter 1 has been brought up to date as many countries de-carbonise their power sector. Chapter 6 (load flow) has been substantially rewritten and voltage source converter HVDC added to Chapter 9. Chapter 10 has been revised to include modern switchgear and protection while recognising that the young engineer is likely to encounter much equipment that may be 30–40 years old. Chapter 12 has been comprehensively revised and now contains material suitable for teaching the fundamentals of the economics of operation and development of power systems. All chapters have been carefully revised and where we considered it would aid clarity the material rearranged. We have paid particular attention to the Examples and Problems and have created Solutions to the Problems that can be found on the Wiley website.

We are particularly indebted to Dave Thompson who created all the illustrations for this edition, Lewis Dale for his assistance with Chapter 12, and to IPSA Power for generously allowing us a license for their power system analysis software. Also we would like to thank: Chandima Ekanayake, Prabath Binduhewa, Predrag Djapic and Jelena Rebic for their assistance with the Solutions to the Problems. Bethany

Corcoran provided the data for Figure 1.1 while Alstom Grid, through Rose King, kindly made available information for some of the drawings of Chapter 11. Although, of course, responsibility for errors and omissions lies with us, we hope we have stayed true to the spirit of this important textbook.

For instructors and teachers, solutions to the problems set out in the book can be found on the companion website www.wiley.com/go/weedy_electric.

Nick Jenkins, Janaka Ekanayake, Goran Strbac
June 2012

Symbols

Throughout the text, symbols in bold type represent complex (phasor) quantities requiring complex arithmetic. Italic type is used for magnitude (scalar) quantities.

$\mathbf{A}$,$\mathbf{B}$,$\mathbf{C}$,$\mathbf{D}$	Generalised circuit constants
a–b–c	Phase rotation (alternatively R–Y–B)
a	Operator $1\angle 120^\circ$
C	Capacitance (farad)
D	Diameter
$\mathbf{E}$	e.m.f. generated
F	Cost function (units of money per hour)
f	Frequency (Hz)
G	Rating of machine
g	Thermal resistivity (°C m/W)
H	Inertia constant (seconds)
h	Heat transfer coefficient (W/m^2 per °C)
$\mathbf{I}$	Current (A)
$\mathbf{I}^*$	Conjugate of $\mathbf{I}$
I_d	In-phase current
I_q	Quadrature current
j	$1\angle 90^\circ$ operator
K	Stiffness coefficient of a system (MW/Hz)
L	Inductance (H)
ln	Natural logarithm
M	Angular momentum (J-s per rad or MJ-s per electrical degree)
N	Rotational speed (rev/min, rev/s, rad/s)
$\mathbf{P}$	Propagation constant ($\alpha + j\beta$)
P	Power (W)
$\frac{\text{d}P}{\text{d}\delta}$	Synchronising power coefficient
p.f.	Power factor
p	Iteration number
Q	Reactive power (VAr)
q	Loss dissipated as heat (W)
R	Resistance (Ω); also thermal resistance (°C/W)
R–Y–B	Phase rotation (British practice)
$\mathbf{S}$	Complex power $= P \pm jQ$
S	Siemens
s	Laplace operator
s	Slip

SCR	Short-circuit ratio
T	Absolute temperature (K)
t	Time
t	Off-nominal transformer tap ratio
Δt	Interval of time
Ω^{-1}	Siemens
U	Velocity
$\mathbf{V}$	Voltage; ΔV scalar voltage difference
V	Voltage magnitude
W	Volumetric flow of coolant (m^3/s)
X'	Transient reactance of a synchronous machine
X''	Subtransient reactance of a synchronous machine
X_d	Direct axis synchronous reactance of a synchronous machine
X_q	Quadrature axis reactance of a synchronous machine
X_s	Synchronous reactance of a synchronous machine
$\mathbf{Y}$	Admittance (p.u. or Ω)
$\mathbf{Z}$	Impedance (p.u. or Ω)
$\mathbf{Z}_0$	Characteristic or surge impedance (Ω)
α	Delay angle in rectifiers and inverters–d.c. transmission
α	Attenuation constant of line
α	Reflection coefficient
β	Phase-shift constant of line
β	$(180 - \alpha)$ used in inverters
β	Refraction coefficient $(1 + \alpha)$
γ	Commutation angle used in converters
δ	Load angle of synchronous machine or transmission angle across a system (electrical degrees)
δ_0	Recovery angle of semiconductor valve
ε	Permittivity
η	Viscosity (g/(cm-s))
θ	Temperature rise (°C) above reference or ambient
λ	Lagrange multiplier
ρ	Electrical resistivity (Ω-m)
ρ	Density (kg/m^3)
τ	Time constant
ϕ	Angle between voltage and current phasors (power factor angle)
ω	Angular frequency (rad/s)

Subscripts 1, 2, and 0 refer to positive, negative, and zero symmetrical components, respectively.

1

Introduction

1.1 History

In 1882 Edison inaugurated the first central generating station in the USA. This fed a load of 400 lamps, each consuming 83 W. At about the same time the Holborn Viaduct Generating Station in London was the first in Britain to cater for consumers generally, as opposed to specialized loads. This scheme used a 60 kW generator driven by a horizontal steam engine; the voltage of generation was 100 V direct current.

The first major alternating current station in Great Britain was at Deptford, where power was generated by machines of 10 000 h.p. and transmitted at 10 kV to consumers in London. During this period the battle between the advocates of alternating current and direct current was at its most intense with a similar controversy raging in the USA and elsewhere. Owing mainly to the invention of the transformer the supporters of alternating current prevailed and a steady development of local electricity generating stations commenced with each large town or load centre operating its own station.

In 1926, in Britain, an Act of Parliament set up the Central Electricity Board with the object of interconnecting the best of the 500 generating stations then in operation with a high-voltage network known as the Grid. In 1948 the British supply industry was nationalized and two organizations were set up: (1) the Area Boards, which were mainly concerned with distribution and consumer service; and (2) the Generating Boards, which were responsible for generation and the operation of the high-voltage transmission network or grid.

All of this changed radically in 1990 when the British Electricity Supply Industry was privatized. Separate companies were formed to provide competition in the supply of electrical energy (sometimes known as electricity retail businesses) and in power generation. The transmission and distribution networks are natural monopolies, owned and operated by a Transmission System Operator and Distribution Network Operators. The Office of Gas and Electricity Markets (OFGEM) was

Electric Power Systems, Fifth Edition. B.M. Weedy, B.J. Cory, N. Jenkins, J.B. Ekanayake and G. Strbac.

established as the Regulator to ensure the market in electricity generation and energy supply worked effectively and to fix the returns that the Transmission and Distribution Companies should earn on their monopoly businesses.

For the first 80 years of electricity supply, growth of the load was rapid at around 7% per year, implying a doubling of electricity use every 10 years and this type of increase continues today in rapidly industrializing countries. However in the USA and in other industrialized countries there has been a tendency, since the oil shock of 1973, for the rate of increase to slow with economic growth no longer coupled closely to the use of energy. In the UK, growth in electricity consumption has been under 1% per year for a number of years.

A traditional objective of energy policy has been to provide secure, reliable and affordable supplies of electrical energy to customers. This is now supplemented by the requirement to limit greenhouse gas emissions, particularly of CO_2, and so mitigate climate change. Hence there is increasing emphasis on the generation of electricity from low-carbon sources that include renewable, nuclear and fossil fuel plants fitted with carbon capture and storage equipment. The obvious way to control the environmental impact of electricity generation is to reduce the electrical demand and increase the efficiency with which electrical energy is used. Therefore conservation of energy and demand reduction measures are important aspects of any contemporary energy policy.

1.2 Characteristics Influencing Generation and Transmission

There are three main characteristics of electricity supply that, however obvious, have a profound effect on the manner in which the system is engineered. They are as follows:

Electricity, unlike gas and water, cannot be stored and the system operator traditionally has had limited control over the load. The control engineers endeavour to keep the output from the generators equal to the connected load at the specified voltage and frequency; the difficulty of this task will be apparent from a study of the load curves in Figure 1.1. It will be seen that the load consists of a steady component known as the base load, plus peaks that depend on the time of day and days of the week as well as factors such as popular television programmes.

The electricity sector creates major environmental impacts that increasingly determine how plant is installed and operated. Coal burnt in steam plant produces sulphur dioxide that causes acid rain. Thus, in Europe, it is now mandatory to fit flue gas desulphurisation plant to coal fired generation. All fossil fuel (coal, oil and gas) produce CO_2 (see Table 1.1) which leads to climate change and so its use will be discouraged increasingly with preference given to generation by low-carbon energy sources.

The generating stations are often located away from the load resulting in transmission over considerable distances. Large hydro stations are usually remote from urban centres and it has often been cost-effective to burn coal close to where it is mined and transport the electricity rather than move the coal. In many countries, good sites for wind energy are remote from centres of population and,

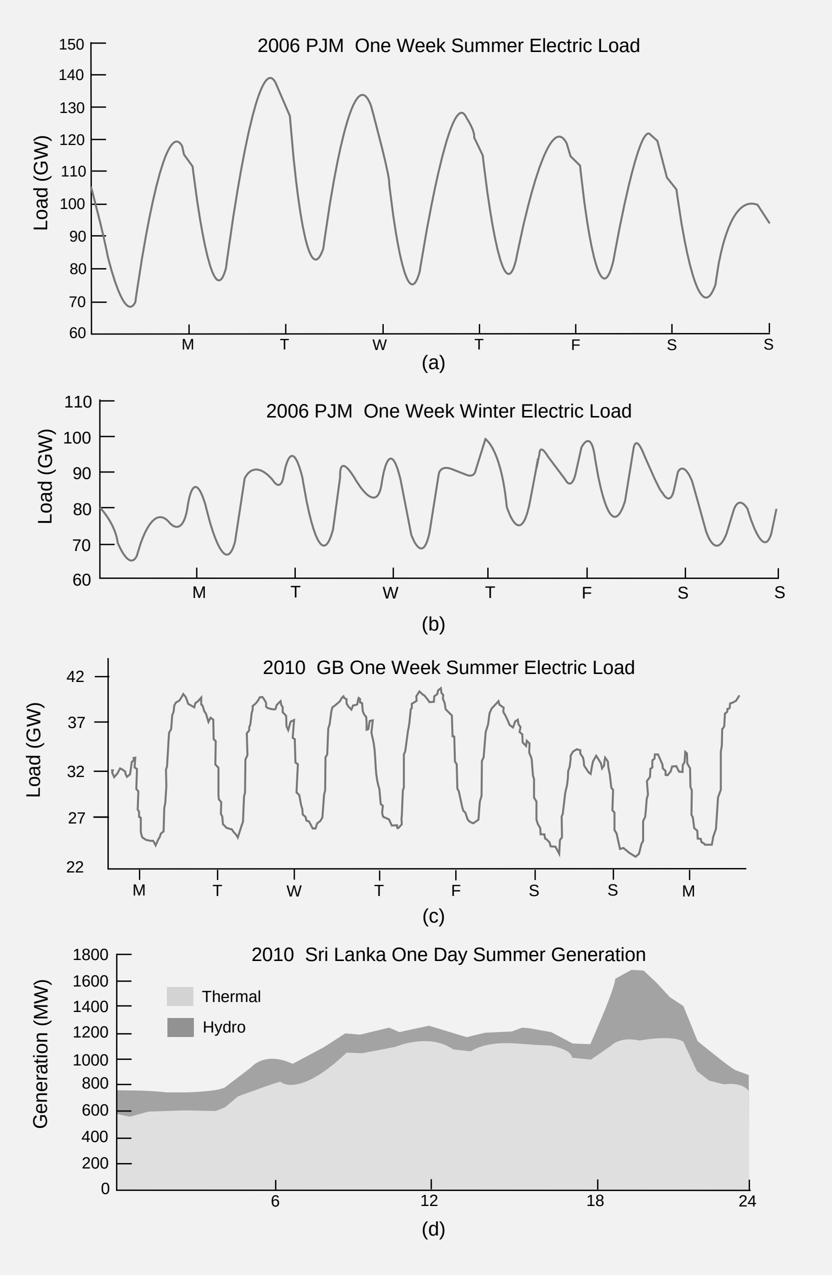


Figure 1.1 Load curves. (a) PJM (Pennsylvania, Jersey, Maryland) control area in the east of the USA over a summer week. The base load is 70 GW with a peak of 140 GW. This is a very large interconnected power system. (b) PJM control area over a winter week. Note the morning and evening peaks in the winter with the maximum demand in the summer. (c) Great Britain over a summer week. The base load is around 25 GW with a daily increase/decrease of 15 GW. GB is effectively an isolated power system. (d) Sri Lanka over 1 day. Note the base load thermal generation with hydro used to accommodate the rapid increase of 500 MW at dusk

although it is possible to transport gas in pipelines, it is often difficult to obtain permission to construct generating stations close to cities. Moreover, the construction of new electrical transmission is subject to delays in many developed countries caused by objections from the public and the difficulty in obtaining permission for the construction of new overhead line circuits.

1.3 Operation of Generators

The national electrical load consists of a base plus a variable element, depending on the time of day and other factors. In thermal power systems, the base load should be supplied by the most efficient (lowest operating cost) plant which then runs 24 hours per day, with the remaining load met by the less efficient (but lower capital cost) stations. In hydro systems water may have to be conserved and so some generators are only operated during times of peak load.

In addition to the generating units supplying the load, a certain proportion of available plant is held in reserve to meet sudden contingencies such as a generator unit tripping or a sudden unexpected increase in load. A proportion of this reserve must be capable of being brought into operation immediately and hence some machines must be run at, say, 75% of their full output to allow for this spare generating capacity, called spinning reserve.

Reserve margins are allowed in the total generation plant that is constructed to cope with unavailability of plant due to faults, outages for maintenance and errors in predicting load or the output of renewable energy generators. When traditional national electricity systems were centrally planned, it was common practice to allow a margin of generation of about 20% over the annual peak demand. A high proportion of intermittent renewable energy generation leads to a requirement for a higher reserve margin. In a power system there is a mix of plants, that is, hydro, coal, oil, renewable, nuclear, and gas turbine. The optimum mix gives the most economic operation, but this is highly dependent on fuel prices which can fluctuate with time and from region to region. Table 1.2 shows typical plant and

Table 1.1 Estimated carbon dioxide emissions from electricity generation in Great Britain

Fuel	Tonnes of CO_2/GWh of Electrical Output
Coal	915
Oil	633
Gas	405
Great Britain generation portfolio (including nuclear and renewables)	452

Data from the Digest of UK Energy Statistics, 2010, published by the Department of Energy and Climate Change.

Table 1.2 Example of costs of electricity generation

Generating Technology	Capital Cost of Plant £/MW	Cost of electricity £/MWh
Combined Cycle Gas Turbine	720	80
Coal	1800	105
Onshore wind	1520	94
Nuclear	2910	99

Data from UK Electricity Generating Costs Update, 2010, Mott MacDonald, reproduced with permission

generating costs for the UK. It is clear some technologies have a high capital cost (for example, nuclear and wind) but low fuel costs.

1.4 Energy Conversion

1.4.1 Energy Conversion Using Steam

The combustion of coal, gas or oil in boilers produces steam, at high temperatures and pressures, which is passed through steam turbines. Nuclear fission can also provide energy to produce steam for turbines. Axial-flow turbines are generally used with several cylinders, containing steam of reducing pressure, on the same shaft.

A steam power-station operates on the Rankine cycle, modified to include superheating, feed-water heating, and steam reheating. High efficiency is achieved by the use of steam at the maximum possible pressure and temperature. Also, for turbines to be constructed economically, the larger the size the less the capital cost per unit of power output. As a result, turbo-generator sets of 500 MW and more have been used. With steam turbines above 100 MW, the efficiency is increased by reheating the steam, using an external heater, after it has been partially expanded. The reheated steam is then returned to the turbine where it is expanded through the final stages of blading.

A schematic diagram of a coal fired station is shown in Figure 1.2. In Figure 1.3 the flow of energy in a modern steam station is shown.

In coal-fired stations, coal is conveyed to a mill and crushed into fine powder, that is pulverized. The pulverized fuel is blown into the boiler where it mixes with a supply of air for combustion. The exhaust steam from the low pressure (L.P.) turbine is cooled to form condensate by the passage through the condenser of large quantities of sea- or river-water. Cooling towers are used where the station is located inland or if there is concern over the environmental effects of raising the temperature of the sea- or river-water.

Despite continual advances in the design of boilers and in the development of improved materials, the nature of the steam cycle is such that vast quantities of heat are lost in the condensate cooling system and to the atmosphere. Advances in design and materials in the last few years have increased the thermal

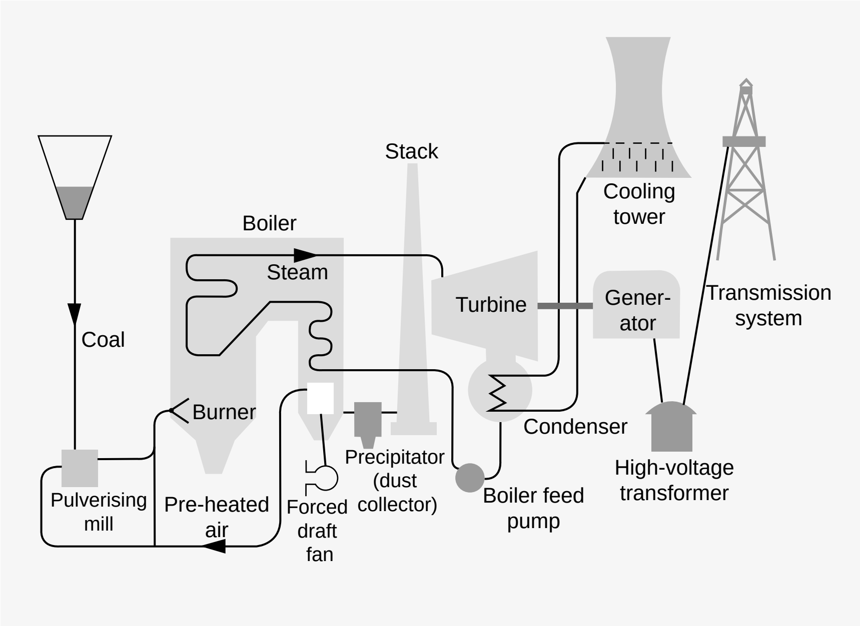


Figure 1.2 Schematic view of coal fired generating station

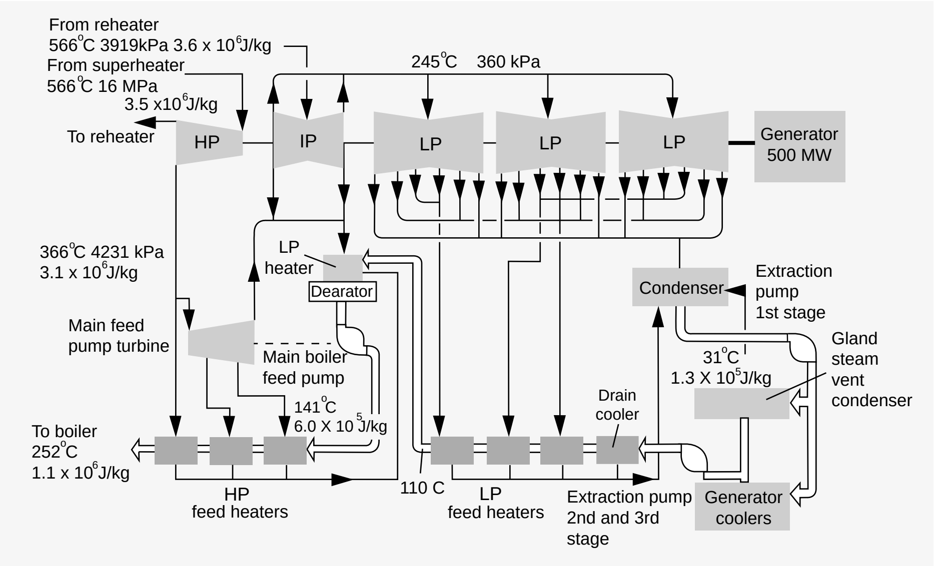


Figure 1.3 Energy flow diagram for a 500 MW turbine generator (Figure adapted from Electrical Review)

efficiencies of new coal stations to approaching 40%. If a use can be found for the remaining 60% of energy rejected as heat, fairly close to the power station, forming a Combined Heat and Power (or Co-generation) system then this is clearly desirable.

1.4.2 Energy Conversion Using Water

Perhaps the oldest form of energy conversion is by the use of water power. In a hydroelectric station the energy is obtained free of cost. This attractive feature has always been somewhat offset by the very high capital cost of construction, especially of the civil engineering works. Unfortunately, the geographical conditions necessary for hydro-generation are not commonly found, especially in Britain. In most developed countries, all the suitable hydroelectric sites are already fully utilized. There still exists great hydroelectric potential in many developing countries but large hydro schemes, particularly those with large reservoirs, have a significant impact on the environment and the local population.

The difference in height between the upper reservoir and the level of the turbines or outflow is known as the head. The water falling through this head gains energy which it then imparts to the turbine blades. Impulse turbines use a jet of water at atmospheric pressure while in reaction turbines the pressure drops across the runner imparts significant energy.

A schematic diagram of a hydro generation scheme is shown in Figure 1.4.

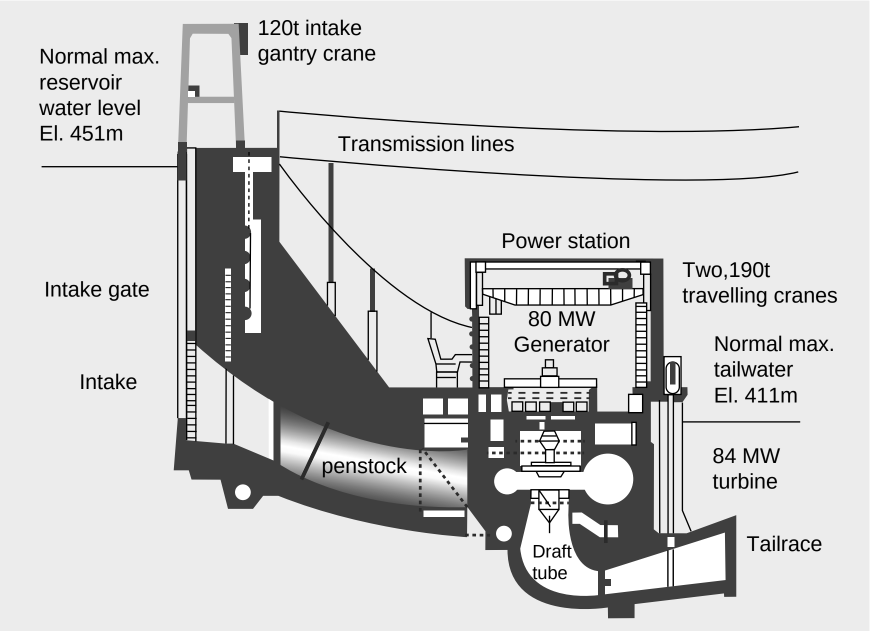


Figure 1.4 Schematic view of a hydro generator (Figure adapted from Engineering)

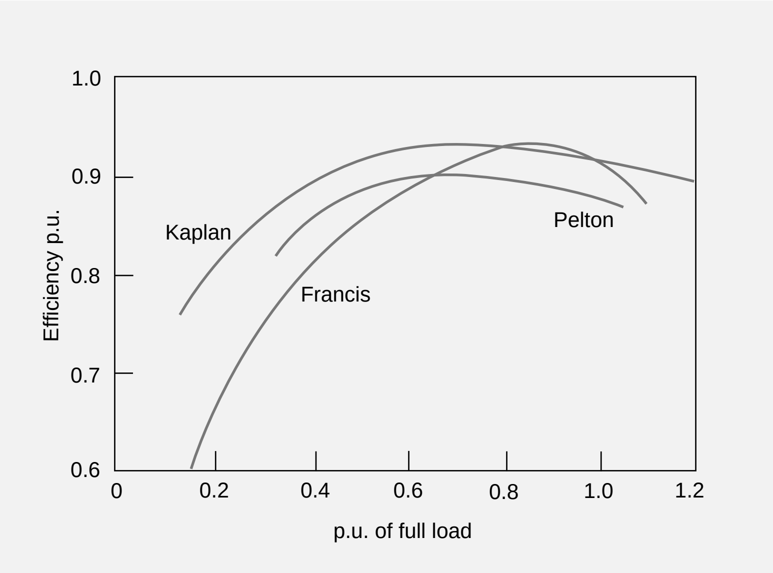


Figure 1.5 Typical efficiency curves of hydraulic turbines (1 per unit (p.u.). = 100%)

Particular types of turbine are associated with the various heights or heads of water level above the turbines. These are:

1. **Pelton:** This is used for heads of 150–1500 m and consists of a bucket wheel rotor with water jets from adjustable flow nozzles.
2. **Francis:** This is used for heads of 50–500 m with the water flow within the turbine following a spiral path.
3. **Kaplan:** This is used for run-of-river stations with heads of up to 60 m. This type has an axial-flow rotor with variable-pitch blades.

Typical efficiency curves for each type of turbine are shown in Figure 1.5. Hydroelectric plant has the ability to start up quickly and the advantage that no energy losses are incurred when at a standstill. It has great advantages, therefore, for power generation because of this ability to meet peak loads at minimum operating cost, working in conjunction with thermal stations – see Figure 1.1(d). By using remote control of the hydro sets, the time from the instruction to start up to the actual connection to the power network can be as short as 3 minutes.

The power available from a hydro scheme is given by

$$P = \rho g Q H \qquad [\mathrm{W}]$$

where

Q = flow rate (m^3/s) through the turbine;
ρ = density of water ($1000\,kg/m^3$);

g = acceleration due to gravity ($9.81\,\mathrm{m/s^2}$);
H = head, that is height of upper water level above the lower (m).

Substituting,

$$P = 9.81QH \qquad \text{[kW]}$$

1.4.3 Gas Turbines

With the increasing availability of natural gas (methane) and its low emissions and competitive price, prime movers based on the gas turbine cycle are being used increasingly. This thermodynamic cycle involves burning the fuel in the compressed working fluid (air) and is used in aircraft with kerosene as the fuel and for electricity generation with natural gas (methane). Because of the high temperatures obtained, the efficiency of a gas turbine is comparable to that of a steam turbine, with the additional advantage that there is still sufficient heat in the gas-turbine exhaust to raise steam in a conventional boiler to drive a steam turbine coupled to another electricity generator. This is known as a combined-cycle gas-turbine (CCGT) plant, a schematic layout of which is shown in Figure 1.6. Combined efficiencies of new CCGT generators now approach 60%.

The advantages of CCGT plant are the high efficiency possible with large units and, for smaller units, the fast start up and shut down (2–3 min for the gas turbine, 20 min for the steam turbine), the flexibility possible for load following, the comparative speed of installation because of its modular nature and factory-supplied units,

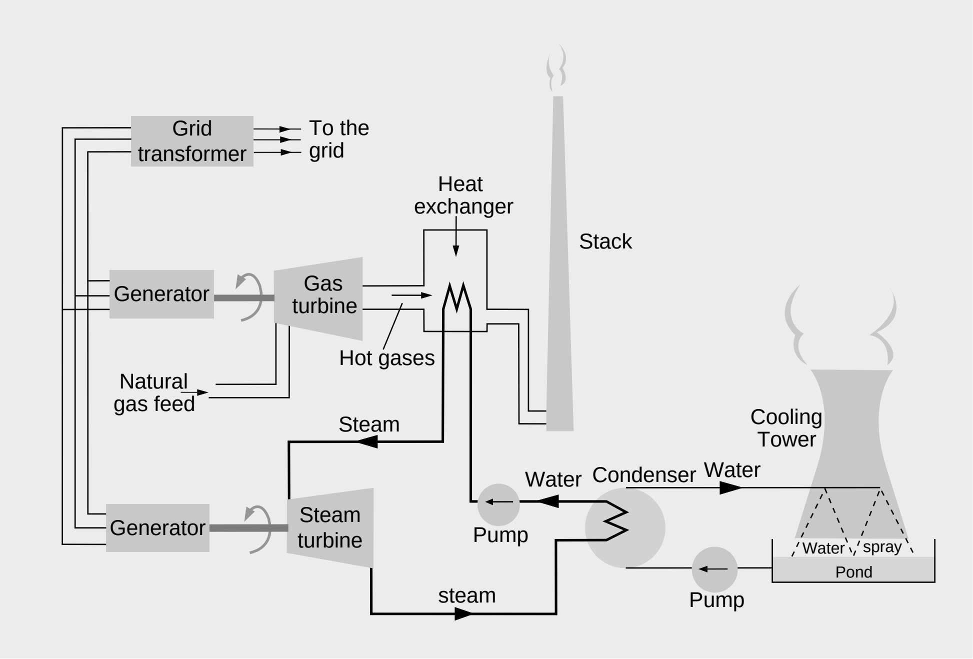


Figure 1.6 Schematic diagram of a combined-cycle gas-turbine power station

and its ability to run on light oil (from local storage tanks) if the gas supply is interrupted. Modern installations are fully automated and require only a few operators to maintain 24 hour running or to supply peak load, if needed.

1.4.4 Nuclear Power

Energy is obtained from the fission reaction which involves the splitting of the nuclei of uranium atoms. Compared with chemical reactions, very large amounts of energy are released per atomic event. Uranium metal extracted from the base ore consists mainly of two isotopes, ^{238}U (99.3% by weight) and ^{235}U (0.7%). Only ^{235}U is fissile, that is when struck by slow-moving neutrons its nucleus splits into two substantial fragments plus several neutrons and 3×10^{-11} J of kinetic energy. The fast moving fragments hit surrounding atoms producing heat before coming to rest. The neutrons travel further, hitting atoms and producing further fissions. Hence the number of neutrons increases, causing, under the correct conditions, a chain reaction. In conventional reactors the core or moderator slows down the moving neutrons to achieve more effective splitting of the nuclei.

Fuels used in reactors have some component of ^{235}U. Natural uranium is sometimes used although the energy density is considerably less than for enriched uranium. The basic reactor consists of the fuel in the form of rods or pellets situated in an environment (moderator) which will slow down the neutrons and fission products and in which the heat is evolved. The moderator can be light or heavy water or graphite. Also situated in the moderator are movable rods which absorb neutrons and hence exert control over the fission process. In some reactors the cooling fluid is pumped through channels to absorb the heat, which is then transferred to a secondary loop in which steam is produced for the turbine. In water reactors the moderator itself forms the heat-exchange fluid.

A number of versions of the reactor have been used with different coolants and types of fissile fuel. In Britain the first generation of nuclear power stations used Magnox reactors in which natural uranium in the form of metal rods was enclosed in magnesium-alloy cans. The fuel cans were placed in a structure or core of pure graphite made up of bricks (called the moderator). This graphite core slowed down the neutrons to the correct range of velocities in order to provide the maximum number of collisions. The fission process was controlled by the insertion of control rods made of neutron-absorbing material; the number and position of these rods controlled the heat output of the reactor. Heat was removed from the graphite via carbon dioxide gas pumped through vertical ducts in the core. This heat was then transferred to water to form steam via a heat exchanger. Once the steam had passed through the high-pressure turbine it was returned to the heat exchanger for reheating, as in a coal- or oil-fired boiler.

A reactor similar to the Magnox is the advanced gas-cooled reactor (AGR) which is still in use in Britain but now coming towards the end of its service life. A reinforced-concrete, steel-lined pressure vessel contains the reactor and heat exchanger. Enriched uranium dioxide fuel in pellet form, encased in stainless steel cans, is used; a number of cans are fitted into steel fitments within a graphite tube to

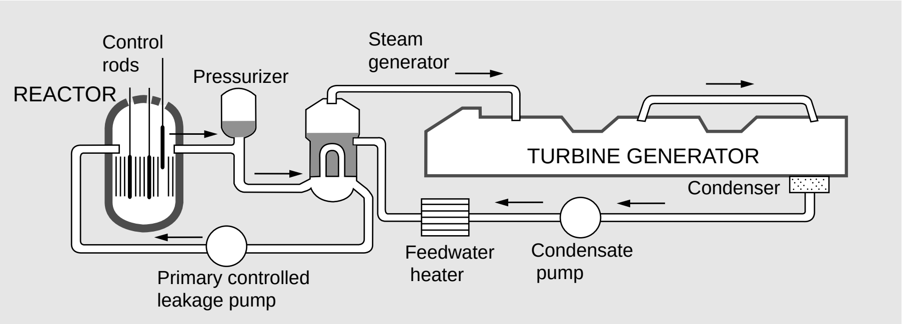


Figure 1.7 Schematic diagram of a pressurized-water reactor (PWR)

form a cylindrical fuel element which is placed in a vertical channel in the core. Depending on reactor station up to eight fuel elements are held in place one above the other by a tie bar. Carbon dioxide gas, at a higher pressure than in the Magnox type, removes the heat. The control rods are made of boron steel. Spent fuel elements when removed from the core are stored in a special chamber and lowered into a pond of water where they remain until the level of radioactivity has decreased sufficiently for them to be removed from the station and disassembled.

In the USA and many other countries pressurized-water and boiling-water reactors are used. In the pressurized-water type the water is pumped through the reactor and acts as a coolant and moderator, the water being heated to 315 °C at around 150 bar pressure. At this temperature and pressure the water leaves the reactor at below boiling point to a heat exchanger where a second hydraulic circuit feeds steam to the turbine. The fuel is in the form of pellets of uranium dioxide in bundles of zirconium alloy.

The boiling-water reactor was developed later than the pressurized-water type. Inside the reactor, heat is transferred to boiling water at a pressure of 75 bar (1100 p.s.i.). Schematic diagrams of these reactors are shown in Figures 1.7 and 1.8. The ratio of pressurized-water reactors to boiling-water reactors throughout the world is around 60/40%.

Both pressurized- and boiling-water reactors use light water.[1] The practical pressure limit for the pressurized-water reactor is about 160 bar (2300 p.s.i.), which limits its efficiency to about 30%. However, the design is relatively straightforward and experience has shown this type of reactor to be stable and dependable. In the boiling-water reactor the efficiency of heat removal is improved by use of the latent heat of evaporation. The steam produced flows directly to the turbine, causing possible problems of radioactivity in the turbine. The fuel for both light-water reactors is uranium enriched to 3–4% ^{235}U. Boiling-water reactors are probably the cheapest to construct; however, they have a more complicated fuel make up with different enrichment levels within each pin. The steam produced is saturated and requires wet-steam turbines. A further type of water reactor is the heavy-water

---

[1] Light water refers to conventional H_2O while heavy water describes deuterium oxide (D_2O).

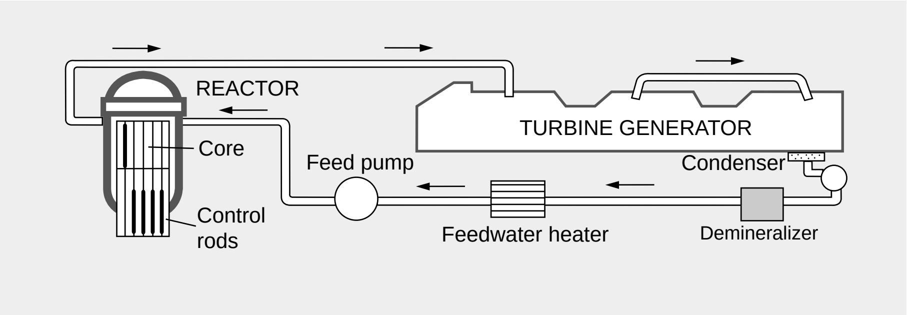


Figure 1.8 Schematic diagram of a boiling-water reactor (BWR)

CANDU type developed by Canada. Its operation and construction are similar to the light-water variety but this design uses naturally occurring, un-enriched or slightly enriched uranium.

Concerns over the availability of future supplies of uranium led to the construction of a number of prototype breeder reactors. In addition to heat, these reactors produce significant new fissile material. However, their cost, together with the technical and environmental challenges of breeder reactors, led to most of these programmes being abandoned and it is now generally considered that supplies of uranium are adequate for the foreseeable future.

Over the past years there has been considerable controversy regarding the safety of reactors and the management of nuclear waste. Experience is still relatively small and human error is always a possibility, such as happened at Three Mile Island in 1979 and Chernobyl in 1986 or a natural event such as the earthquake and tsunami in Fukishima in 2011. However, neglecting these incidents, the safety record of power reactors has been good and now a number of countries (including Britain) are starting to construct new nuclear generating stations using Light Water Reactors. The decommissioning of nuclear power stations and the long term disposal of spent fuel remains controversial.

1.5 Renewable Energy Sources

There is considerable international effort put into the development of renewable energy sources. Many of these energy sources come from the sun, for example wind, waves, tides and, of course, solar energy itself. The average peak solar energy received on the earth's surface is about 600 W/m^2, but the actual value, of course, varies considerably with time of day and cloud conditions.

1.5.1 Solar Energy–Thermal Conversion

There is increasing interest in the use of solar energy for generating electricity through thermal energy conversion. In large-scale (central station) installations the sun's rays are concentrated by lenses or mirrors. Both require accurately curved surfaces and steering mechanisms to follow the motion of the sun. Concentrators may