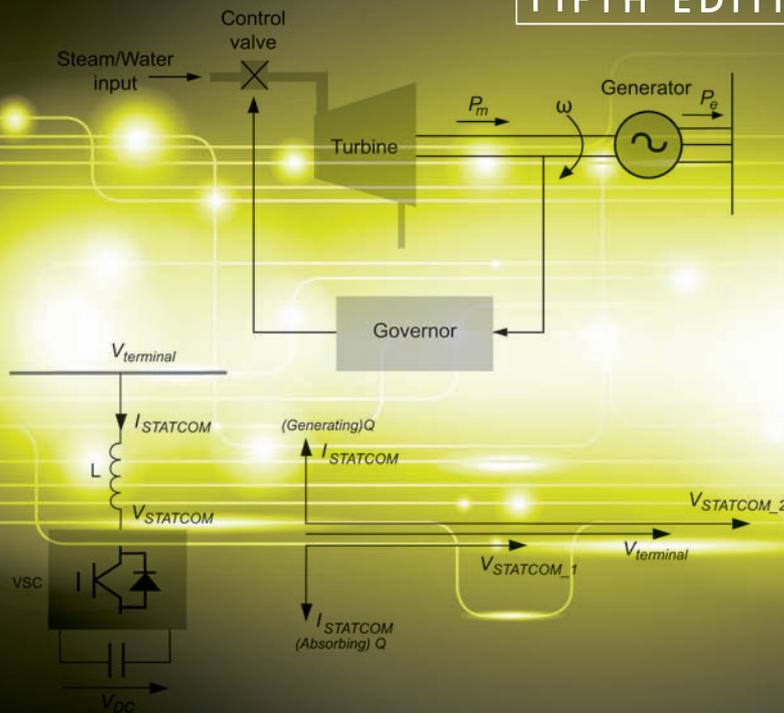


Electric Power Systems

FIFTH EDITION



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

 WILEY

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Fifth Edition

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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.

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

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 CO₂, 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 CO₂ (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,

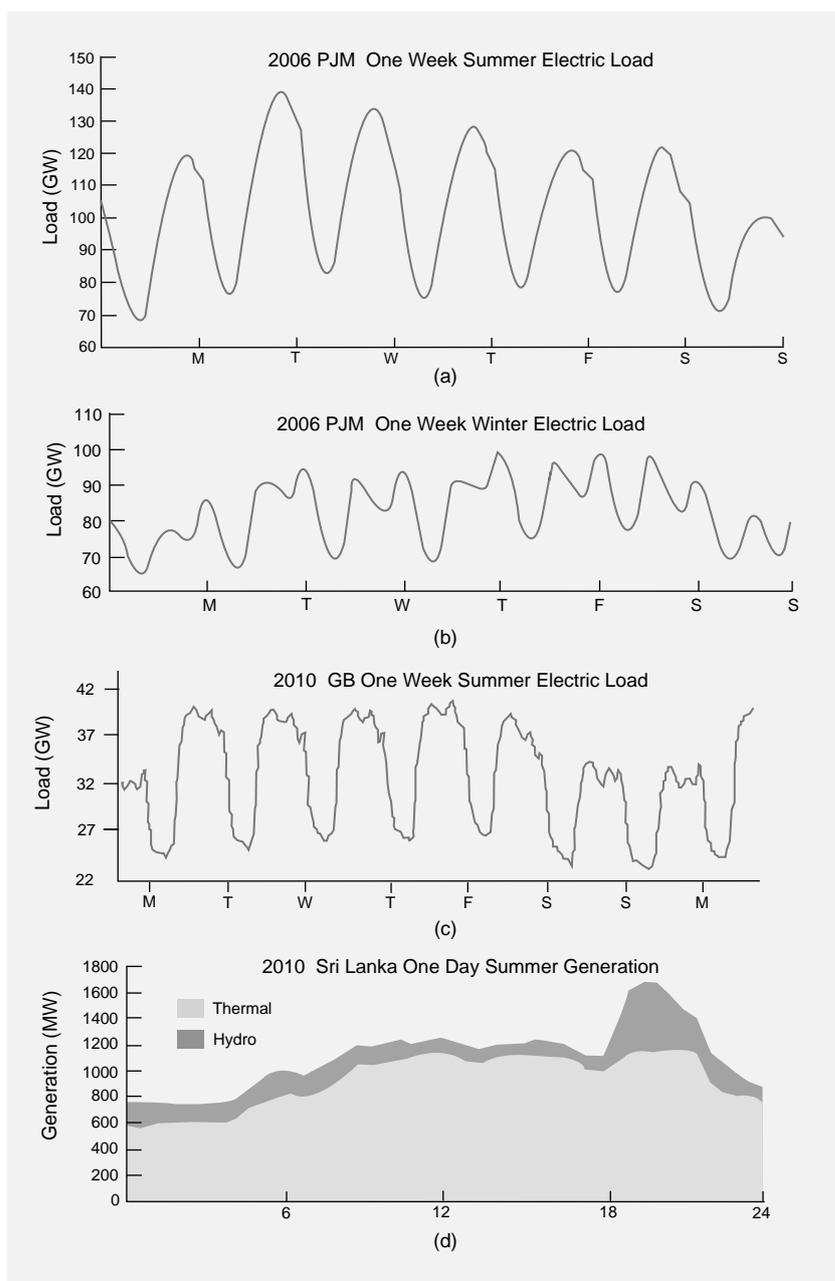


Figure 1.1 Load curves. (a) PJM (Pennsylvania, Jersey, Maryland) control area in the east of the USA over a summer week. The base load is 70 GW with a peak of 140 GW. This is a very large interconnected power system. (b) PJM control area over a winter week. Note the morning and evening peaks in the winter 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

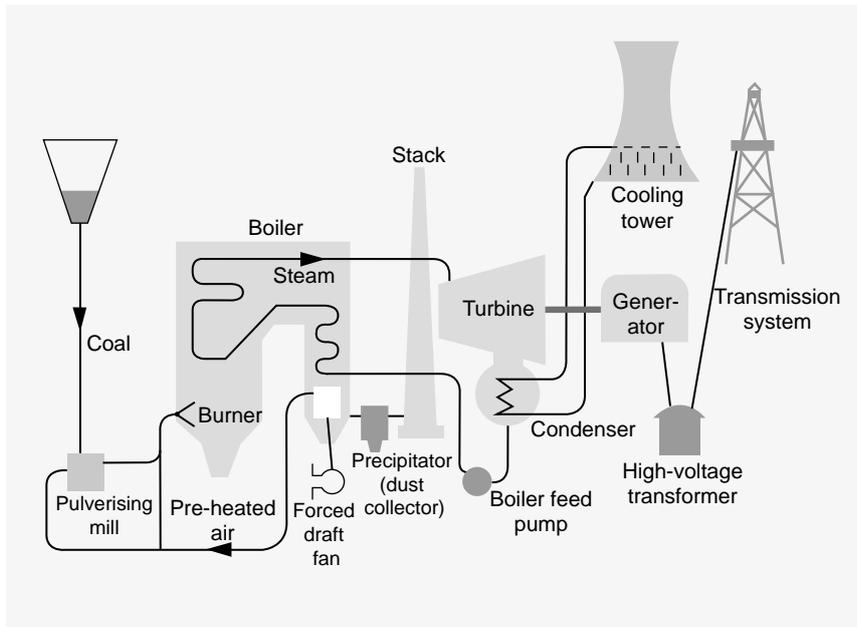


Figure 1.2 Schematic view of coal fired generating station

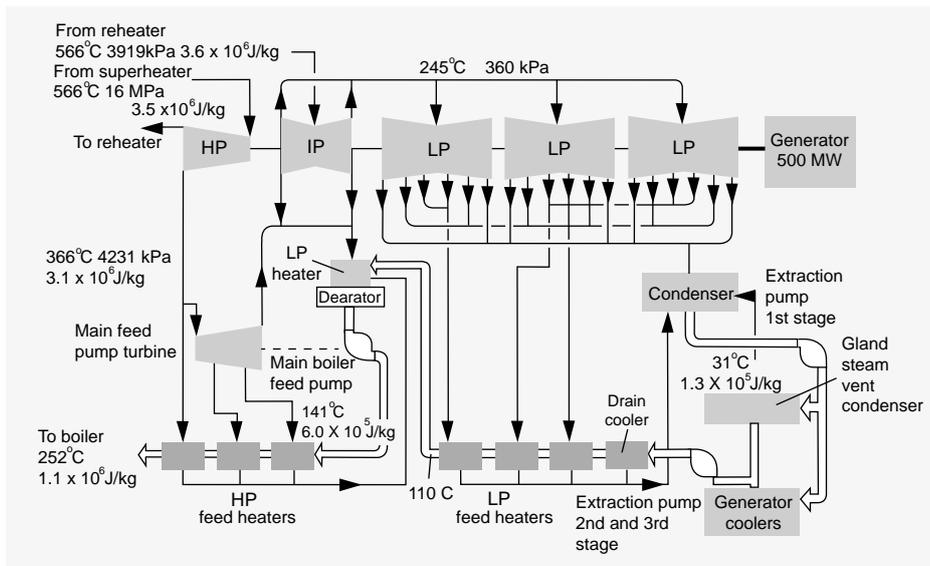


Figure 1.3 Energy flow diagram for a 500 MW turbine generator (Figure adapted from Electrical Review)

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