ELBS

Generation, Transmission and Utilization of Electrical Power

Fourth Edition

A T Starr

LOW-PRICED EDITION

GENERATION, TRANSMISSION AND UTILIZATION OF ELECTRICAL POWER

BY

A. T. STARR

M.A., Ph.D., C.Eng., F.I.E.E.

FOURTH EDITION

THE ENGLISH LANGUAGE BOOK SOCIETY
AND
PITMAN PUBLISHING

Fourth Edition 1957
ELBS edition first printed 1962
Reprinted 1969
Reprinted 1971
Reprinted 1972
Reprinted 1973

SIR ISAAC PITMAN AND SONS LTD.
Pitman House, Parker Street, Kingsway, London, WC2B 5PB
P.O. Box 46038, Banda Street, Nairobi, Kenya

SIR ISAAC PITMAN (AUST.) PTY. LTD.
Pitman House, 158 Bouverie Street, Carlton, Victoria 3053, Australia

PITMAN PUBLISHING CORPORATION
6 East 43rd Street, New York, N.Y. 10017, U.S.A.

SIR ISAAC PITMAN (CANADA) LTD.
495 Wellington Street West, Toronto 135, Canada

THE COPP CLARK PUBLISHING COMPANY
517 Wellington Street West, Toronto 135, Canada

ISBN: 0 273 40149 1

Reproduced and printed by photolithography and bound in
Great Britain at The Pitman Press, Bath

G3—(T.1506:7)

GENERATION, TRANSMISSION AND UTILIZATION OF ELECTRICAL POWER

Some ELBS Low-priced Textbooks

BENSON, F. A. and HARRISON, D.	*Electric-Circuit Theory*	Edward Arnold
BLAKEY, J.	*University Mathematics*	Blackie
BUCHAN, M. F.	*Electricity Supply*	Edward Arnold
CLAYTON, A. E. and HANCOCK, N. N.	*The Performance and Design of DC Machines*	Pitman
COTTON, H.	*Advanced Electrical Technology*	Pitman
DOVER, A. T.	*Electric Traction*	Pitman
FRANCIS, T. G.	*Electrical Installation*	Longman
GEARY, A., LOWRY, H. V. and HAYDEN, H. A.	*Mathematics for Technical Students*, Vol. III	Longman
GOLDING, E. W. and WIDDIS, F. C.	*Electrical Measurement and Measuring Instruments*	Pitman
HINDMARSH, J.	*Electrical Machines and their Applications*	Pergamon
HUGHES, E.	*Electrical Technology*	Longman
MORLEY, A. and HUGHES, E.	*Principles of Electricity*	Longman
PADDOCK, J. O. and GALVIN, R. A. W.	*Electrical Installation Technology and Practice*	English Universities Press
RENTON, R. N.	*Elementary Telecommunication Principles*	Pitman
SHEPHERD, J., MORTON, A. H. and SPENCE, L.	*Higher Electrical Engineering*	Pitman
SPAIN, B.	*Vector Analysis*	Van Nostrand, London
SPOONER, D. F. and GRINSTED, W. H.	*Mathematics for Telecommunications and Electrical Engineering*, Vols. I/II	English Universities Press

PREFACE TO THE FOURTH EDITION

THE use of electrical power is increasing rapidly and resources of coal and oil are not likely to meet requirements for more than fifty to a hundred years. For these and other reasons there is an overwhelming drive to use nuclear energy, and massive development is under way. An additional Appendix gives a qualitative explanation of the present method of utilizing nuclear (or atomic) energy, and there is an outline of the Calder Hall station in Chapter I.

The other main alterations are in Chapter I and are concerned with generation.

A. T. STARR

NEW BARNET, 1956

PREFACE TO THE FIRST EDITION

THE main purpose with which this book was written was to present the student, who is studying for the Engineering Degrees, the Faraday House Diploma, the National Diploma, or the National Certificate, with a single book containing a description of the syllabus known as "Electric Power." The syllabus is so wide that a choice must be made, not only as regards the matter to be included, but also as to the depth of treatment of those parts that have been dealt with. The author hopes that his choice is reasonable, and that the inclusion of many illustrations and much descriptive matter will make the book interesting and acceptable.

The author wishes to thank the various manufacturers, editors, and writers for permission to include published material; and his colleagues Messrs. A. Regnauld, S. O. Pearson, A. N. Arman, and E. J. Keefe for much help by reading, criticizing, and correcting the manuscript and proofs.

Finally, the author desires to thank the Technical Editor to Sir Isaac Pitman & Sons and Mr. W. F. Floyd for eliminating obscurities and errors from the text.

A. T. STARR

FARADAY HOUSE
July, 1937

CONTENTS

CHAPTER X

CHAPTER XI

CHAPTER XII

CHAPTER XIII

CHAPTER XIV

APPENDIXES

CHAPTER I

GENERATION OF ELECTRICAL ENERGY

Sources of Energy. Modern civilization differs from earlier civilizations in the enormous use of energy produced by machines. The results are a diminution of mechanical drudgery, a shorter working day, a higher standard of living, a healthier and more balanced diet (since food can be transported easily from one end of the world to another), and freedom to a large extent from local famines. There is a close relation between the energy used per person and the standard of living.

Within the last thirty years there has been a rapid increase in the generation of electrical energy, and the following table gives values for Great Britain.

TABLE I

ELECTRICITY CONSUMPTION IN GREAT BRITAIN

(In Milliard units, i.e. 10^9 kWh.)

	1925	1950	1954 (estimated)	1965 (forecast)	1975
Domestic and agricultural . .	0·6	14·9	19·6	37	63
Industrial and traction . .	5·1	31·0	42·9	79	138
Total sales	5·7	45·9	62·5	116	201
Total generated . . .	6·4	51·9	69	130	223

In 1953–4 the consumption per head in Great Britain was about 1 300 kWh./annum, whilst in Norway it was 4 300, and in the U.S.A. 2 900. It is fairly certain, therefore, that the rate of increase shown in the table is conservative.

The primary source of energy is the Sun. Direct utilization of solar radiation, which has been estimated to be equivalent to 5 000 h.p. per acre at noon in summer, has been made in Egypt, where in a certain installation the mirror to boiler surface ratio is $4\frac{1}{2} : 1$, the boiler efficiency is 40 per cent, and the plant develops 63 b.h.p. per acre. The method is inconvenient as it requires a large area and the absence of clouds, but has probably a sphere of use in irrigation and other pumping services.

The energy of winds, produced by the Sun, has been used for many hundreds of years in windmills, and can be used to drive small generators, which charge up storage batteries for continuous use. Efficient generators are being designed in this country.

The main sources of energy are fuels, viz. coal and oil, and water power, viz. water at a high level and tides. The utilization of the energy of fuel is possible by means of steam and internal combustion engines and the turbine; but the harnessing of water power has been made possible by the electrical transmission of energy which alone can transmit the energy from the places where the water power occurs to where the energy is needed.

The internal combustion engine using petrol is suitable for mobile units, such as road traffic and small craft for river and seashore work, and recently the Diesel engine using heavy oil has been adapted to the same purpose. The latter is also replacing coal- and oil-fired steam plants for marine propulsion, but even so it has been found advantageous to use an electrical conversion in some cases.

A new form of liberating energy was devised in World War II by the fission (or nuclear disintegration) of uranium. The energy released in this way is converted to heat, which may then be used to drive steam turbines. Development is proceeding in the U.S.A. and Great Britain, where bulk supplies of energy are expected to be available in 1962. The method is known as that of *atomic energy*.

The conversion of the heat of combustion of coal and oil and of nuclear fission into electrical energy, and the distribution of the latter, afford advantages which will be discussed later.

Heat and Mechanical Energy. There are several units of heat and of mechanical energy, and it is useful to list their values and relationships. The *calorie* (cal.) is the amount of heat required to raise the temperature of 1 g. of water by 1° C.: the *Calorie* or *kilo-calorie* (k.cal. or Cal.) is 1 000 times as great, and is the unit used when nutrition is discussed, e.g. an intake of 2 000 to 3 000 Calories per day is desirable for an adult. The British unit of heat is the *British Thermal Unit* (B.Th.U.) which raises the temperature of 1 lb. of water by 1° F. Since 1 lb. = 453·6 g. and 1° F. = (5/9)° C., it follows that

$$1 \text{ B.Th.U.} = 252 \text{ cal.} = 0{\cdot}252 \text{ k.cal.} \qquad (1.1)$$

In dealing with large resources of energy it has been found convenient to introduce a large unit of heat denoted by Q, where

$$1 \text{ Q} = 10^{18} \text{ B.Th.U.} \qquad (1.2)$$

The experiments of Joule and Robert Mayer established the fact that heat and mechanical energy are interchangeable, one unit of heat producing a fixed amount of mechanical energy, and vice versa. The relation between them is called the *mechanical equivalent of heat*, and is given as

$$\left.\begin{array}{ll} & 1 \text{ B.Th.U.} = 778 \text{ ft. lb.} \\ \text{or} & 1 \text{ cal.} = 4{\cdot}18 \,.\, 10^7 \text{ erg.} = 4{\cdot}18 \text{ J (joule)} \end{array}\right\} \qquad (1.3)$$

The units of power are the *watt* (W.) and the *horse power* (h.p.) where

$$\left.\begin{aligned} &1 \text{ W.} = 10^7 \text{ erg./sec.} = 1 \text{ J/sec.} \\ \text{and} \quad &1 \text{ h.p.} = 550 \text{ ft. lb./sec.} = 746 \text{ W.} \end{aligned}\right\} \quad . \quad . \quad (1.4)$$

The relation between the h.p. and the watt follows from the facts that 1 lb. = 453·6 g. and 1 ft. = 12 × 2·54 cm. The electrical unit of energy is the *kilowatt-hour* (kWh.) and it is seen that

$$\left.\begin{aligned} 1 \text{ kWh.} &= (3\,600)\,(1\,000) \text{ W. sec.} = 3{\cdot}6\,.\,10^6 \text{ joule} \\ &= 8{\cdot}6\,.\,10^5 \text{ cal.} = 3\,412 \text{ B.Th.U.} \end{aligned}\right\} \quad (1.5)$$

$$1 \text{ milliard} = 10^9 \text{ kWh.} = 3{\cdot}4\,.\,10^{12} \text{ B.Th.U.}$$

Heat Value of Coal, Oil, Gas, and Uranium. The heat value of coal varies with the grade: in this country an average value is 12 000 B.Th.U. per lb. If all of the heat could be converted into electrical energy, 1 kWh. would require (3 412/12 000) = 0·28 lb. of coal: the thermal efficiency in a power station had an average value of 23·7 per cent in 1954, so that 1·2 lb. coal is used per kWh. generated. The highly efficient Portobello H.P. had an efficiency of 31·27 per cent in 1954, so that it requires 0·89 lb. coal per kWh. Lignite has a heating value of 4 800 B.Th.U. per lb. and peat has 6 300 B.Th.U. per lb. It is common to express large heat units in terms of tons of coal of heat value 12 000 B.Th.U. per lb.; thus

$$\left. 1 \text{ Q} = \frac{10^{18}}{12\,000 \times 2\,240} \text{ tons} = 37\,000 \text{ megatons} \right\} \quad . \quad (1.6)$$

$$1 \text{ milliard} = 0{\cdot}55 \text{ megatons or about } 0{\cdot}6 \text{ megatons}$$

Heavy oils have a heat value of 20 000 B.Th.U. per lb., so that only three-fifths by weight is required as compared with coal. Quite a number of oil-burning stations produce 1 kWh. per 0·65 lb. of oil, the thermal efficiency being between 25 and 30 per cent, which is greater than for all but the best coal-burning stations. Light oils have a heat value of about 15 000 B.Th.U. per lb.

Coal gas has a heat value of 550 B.Th.U. per ft.^{3} and Mond producer gas has 160 B.Th.U. per ft.^{3}

The heat value of uranium depends upon the method used. Natural uranium contains 99·3 per cent of ^{238}U and 0·7 per cent ^{235}U, the latter being spontaneously fissile while the former is split by the slow released neutrons, in the way described in Appendix VIII. In the simplest method one ton of uranium will produce 3 000 MW. days of energy, which is equivalent to the heat value of about 10 000 tons of coal. By re-cycling the uranium and the produced plutonium, one ton of uranium should produce heat equivalent to 100 000 tons of coal. Eventually the use of fast breeder reactors should make one ton of uranium equivalent to 1 000 000 tons of coal.

Energy Resources and Production. The world supply of coal and oil is not known with any degree of certainty, and there is a tendency to be conservative in estimates. An estimate in 1920 was of the order of $7{\cdot}3 \,.\, 10^{12}$ tons or 200 Q, but it is becoming increasingly difficult to mine much of these resources. It is estimated that the world reserves of uranium and thorium have a heat value of 1 700 Q, which is about ten times that of coal, oil and gas combined. Table II shows the demand for primary fuel in Great Britain, and Table III shows the coal equivalent of the electricity demand based on Table I.

TABLE II

DEMAND FOR PRIMARY FUEL
(Megatons Coal Equivalent)

	1954	1965	1975	1985
Industry . . .	118	156	196	237
Railways and transport .	32	35	36	38
Domestic . . .	65	73	83	94
Total . . .	254	311	373	440

TABLE III

ELECTRICITY DEMAND

	1954	1965	1975	1985
Equivalent megatons .	42	71	104	145
Plant MW. . . .	20 000	38 000	58 000	82 000

In 1985 about 450 megatons will be required. It is expected that coal may provide 225 megatons, oil 150 megatons, hydro-electric power 5 to 10 megatons, and so nuclear power will have to supply about 70 megatons, which corresponds to about 38 000 MW. of nuclear power station capacity. Table IV shows the power and energy required from nuclear fission (estimated September, 1955).

TABLE IV

NUCLEAR FISSION POWER AND ENERGY REQUIRED

	1965	1970	1975	1980
Energy (milliard)	25	40	86	146
Power (MW., 75% load factor) .	3 900	6 200	13 200	23 000

Electrical Transmission of Energy. The conversion of heat into mechanical energy and the electrical transmission of the latter afford many advantages. Electrical transmission is convenient, clean, cheap, and extremely flexible. The extreme cleanliness accompanying the use of electrical energy is very important, when one bears in mind the damage due to smoke and soot. The considerably decreased severity of fogs in London during the last decade or two has been ascribed in part to the decreased burning of coal consequent upon the increase in the use of electricity for heating. The all-electric house keeps much cleaner and requires less frequent re-decoration than a house which uses gas and coal, and these facts must be remembered when one compares the costs of using coal or gas or electricity.

In the realm of lighting, for streets and home, electricity is unrivalled in convenience and cheapness.

For cleanliness, ease of manipulation, and flexibility the electric motor is supreme, so that the use of electrical energy in industry is rapidly increasing.

Electric traction is particularly suitable for dense suburban traffic where quick starting and braking are imperative, whilst it is essential for underground traffic.

Water power is fairly easily converted into electrical power which can then be transmitted to places distant from the source; by proper choice of the site of the hydro-electric installation the power is continuously available. A new and inexhaustible source of power is thus opened up, of which a rapidly increasing use is being made. Oil is needed for road transport and shipping, and coal is likely to be required for the production of oil by hydrogenation, so that the economic advantages of hydro-electric generation will probably increase in the future.

STEAM POWER STATIONS

In a steam power station the fuel, which is coal or lignite or peat, gives up its heat of combustion to a boiler which delivers steam at a high temperature and a high pressure to the steam turbines. The steam loses heat energy in driving the turbine, which is coupled directly or through gearing to an electrical generator. The *thermal efficiency* is the ratio of the heat equivalent of the mechanical energy transmitted to the turbine shaft, to the heat of combustion; it may reach a value of 30 per cent in a very efficient plant. Then there are the losses in the alternator, so that the *overall efficiency*, which is the ratio of the heat equivalent of the electrical output to the heat of combustion, is slightly lower.

As an example we may take the case of the Battersea Power Station. 1 lb. of coal has a heat value of 11 500 B.Th.U. and delivers 3 498 B.Th.U. to the coupling, so that the thermal efficiency is