

Electric Power Transmission Systems

Second Edition

J. ROBERT EATON

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Library of Congress Cataloging in Publication Data

Eaton, J. Robert (James Robert), 1902-
Electric power transmission systems.

Includes index.

I. Electric power systems. I. Cohen, Edwin,
1934- II. Title.
TK1001.E27 1983 621.31'9 82-21514
ISBN 0-13-247304-6

Editorial/production supervision and
interior design: *Shari Ingerman*
Manufacturing buyer: *Gordon Osbourne*

© 1983, 1972 by Prentice-Hall, Inc., Englewood Cliffs, New Jersey 07632

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Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-247304-6

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*
Whitehall Books Limited, *Wellington, New Zealand*

Preface

This book is intended to give a first-level presentation of the technical aspects exhibited by electric systems which transmit power from the generators to the loads. It should be of value to the technologist who builds, maintains, and operates electric power equipment; to the student engineer who later goes on to more advanced study in preparation for design and analysis of power systems; and to those persons whose technical problems are closely associated with the electric power industry.

This second edition of the book is an expanded version of the first one, laying greater emphasis on those aspects of power systems which concern a broader spectrum of engineers and technologists in the performance of their tasks. In particular, the calculation of short-circuit currents due to symmetrical faults and its impact on the ratings of circuit-interrupting devices have been expounded. Besides, a new chapter on distribution has been added, the analytical determination of transmission-line voltages has been stressed, and the load-flow problem has been introduced.

Problems have been added in this edition requesting the student to use a computer for their solution. Some are simple enough to be solved with a hand-held programmable calculator; others are more involved requiring the formation of a data base; a few require an iterative algorithm. It is hoped that these problems will spur the student to a greater use of the computational facilities at his disposal.

It is assumed that the reader has had a basic course in electric circuit theory. His or her knowledge of mathematics should include elementary

algebra and calculus, and complex numbers. Chapter 2 summarizes most of the relations used in the remainder of the book.

The first edition of the book was produced by the first author under the sponsorship of the American Electric Power System. The second edition was prepared by the second author while on sabbatical leave from his institute.

The authors acknowledge the assistance of many organizations that made available data presented in this book.

The Indiana and Michigan Electric Company provided many photographs and circuit diagrams.

Public Service Indiana provided photographs of an ac generator and a damaged circuit breaker.

Westinghouse Electric Corporation provided tables of overhead line constants, data on transformer impedances, and a photograph of programmable controller.

Anaconda Wire and Cable Company supplied pictures of typical overhead and underground cables.

The Institute of Electrical and Electronics Engineers granted permission for publication of a table of machine reactances from ANSI/IEEE Standards.

Some of the diagrams of circuit breakers are adaptations of more detailed diagrams published in bulletins of Allis Chalmers Manufacturing Company and General Electric Company.

Edwin Cohen

Contents

	PREFACE	xiii
chapter	THE ELECTRIC POWER SYSTEM	1
1	1-1 Requirements of an Electric Supply System 1	
	1-2 Minimum Power System 4	
	1-3 More Complicated Systems 8	
	1-4 Some Typical System Layouts 13	
	1-5 Hazards to Power-System Operation 14	
	1-6 Need for Auxiliary Equipment 15	
	1-7 One-Line and Three-Line Diagrams 18	
	1-8 Some Typical Power-System Diagrams 19	
	1-9 Communication Systems 23	
chapter	FUNDAMENTALS OF ELECTRIC CIRCUITS	24
2	2-1 Purpose 24	
	2-2 System of Units 24	
	2-3 Notation 25	
	2-4 Electric-Circuit Relations 26	
	*2-5 Relations Pertaining to AC Circuits 35	
	2-6 Network Relations 48	
	2-7 Three-Phase Circuits 53	
	2-8 Equivalent Circuits of Machines 57	
	Problems 60	

chapter	THE BASIC POWER CIRCUIT	65
3	3-1 The Basic Circuit and Some Applications 65 3-2 Systems to Which the Basic Circuit Applies 66 3-3 Equations of the Basic Power Circuit 68 3-4 Phasor Diagrams 68 3-5 Transmission Diagrams 75 3-6 Losses and Thermal Limits 79 3-7 Balanced Three-Phase Circuit Analysis 82 3-8 Single-Phase Equivalent of a Three-Phase System 85 3-9 Transmission-Line Equivalence; a Better Circuit Model 87 Problems 90	
chapter	PERCENT AND PER UNIT QUANTITIES	93
4	4-1 Introduction 93 4-2 The Percent System 93 4-3 The Per Unit System 95 4-4 Specification of Generators 96 4-5 Specification of Transformers 98 4-6 Specification of Lines and Cables 100 4-7 Change of Base 100 4-8 An Example System 101 4-9 Three-Phase Systems; Per Unit Analysis 103 4-10 Base Quantities in Terms of Kilovolts and Kilovolt-Amperes 106 Problems 107	
chapter	CIRCUIT CONSTANTS	110
5	5-1 Introduction 110 5-2 Overhead Lines 111 5-3 Cables—Portable, Overhead, Underground 125 5-4 Characteristics of Synchronous Machines 128 5-5 Transformer Characteristics 128 5-6 Characteristics of Induction Motors 129 Problems 130	
chapter	ASSEMBLIES OF POWER SYSTEM COMPONENTS	132
6	6-1 Introduction 132 6-2 Four-Terminal Networks—Special Case 133 6-3 Four-Terminal Networks; A , B , C , D Constants 139	

- 6-4 Transmission Diagrams Derived from *ABCD* Constants 151
- 6-5 Graphical Analysis of the Four-Terminal Network 154
- 6-6 Systems with Several Sources 165
- Problems 167

chapter

POWER LIMITS—STABILITY**171****7**

- 7-1 Statement of the Problem 171
- 7-2 Asynchronous Loads (Lamps, Heaters, Induction Motors) 173
- 7-3 Synchronous Loads 175
- 7-4 The Infinite Bus 176
- 7-5 Generator Connected to Infinite Bus 176
- 7-6 Infinite Bus Supplying a Synchronous Motor 183
- 7-7 Stability Analysis from Generalized Constants *ABCD* 184
- 7-8 Transmission Diagram of a Long Transmission Line 185
- 7-9 Methods of Increasing Transmission-System Capabilities 187
- 7-10 Transient Stability 192
- 7-11 Systems with Many Machines 194
- Problems 194

chapter

FAULTS ON POWER SYSTEMS**197****8**

- 8-1 Description of a Fault 197
- 8-2 Need for Calculating Fault Conditions 200
- 8-3 Fault Conditions from Circuit Parameters 202
- 8-4 Synchronous Machine Impedance 210
- 8-5 DC Offset 211
- 8-6 Duties of Circuit-Interrupting Devices 214
- 8-7 Unsymmetrical Faults on Three-Phase Systems 217
- Problems 219

chapter

CIRCUIT-INTERRUPTING DEVICES**222****9**

- 9-1 Types and Ratings 222
- 9-2 The Circuit-Interrupting Process 223
- 9-3 Conduction Process 225
- 9-4 Ionizing Processes 228
- 9-5 Deionizing Processes 229
- 9-6 Arcs and Arc Interruption 231
- 9-7 Circuit-Breaker Designs 235
- 9-8 Fuses 242

- 9-9 Recovery Voltage 243
- 9-10 Circuit-Breaker Characteristics 249
- 9-11 Fuse Characteristics 251
- Problems 255

chapter

SYSTEM INSTRUMENTATION**257****10**

- 10-1 System Monitoring 257
- 10-2 Instruments for System Monitoring 259
- 10-3 Instrument Circuits 260
- 10-4 Voltage Supply to Instruments 261
- 10-5 Current Supply to Instruments 264
- Problems 268

chapter

RELAYS AND RELAY SYSTEMS**270****11**

- 11-1 General 270
- 11-2 Basic Relay Types 271
- 11-3 Relay Timing 274
- 11-4 Relay System Examples 275
- 11-5 Functional Relay Types 278
- 11-6 Relay Connections to Power Equipment 291
- 11-7 Protection of Generators 293
- 11-8 Bus Protection 298
- 11-9 Transformer Protection 299
- 11-10 Relay Protection of Lines 301
- 11-11 Solid-State Relaying 311
- Problems 315

chapter

ELECTRICAL INSULATION**317****12**

- 12-1 Purpose 317
- 12-2 Insulating Materials 318
- 12-3 Insulation Behavior 318
- 12-4 Limitations on Design 326
- 12-5 Sources of Overvoltages 327
- 12-6 Traveling Waves 332
- 12-7 Lightning Arresters 342
- 12-8 Transmission-Line Insulation 345
- Problems 347

chapter

GROUNDING ELECTRIC CIRCUITS EFFECTIVELY 349**13**

- 13-1 Grounding Practice 349
- 13-2 Ground Resistance 351
- 13-3 Expressions for Ground Resistance 353

13-4	Practical Values of Resistivity	353
13-5	Hazards Associated with Current Flow to Ground	357
13-6	A Two-Electrode Ground System	359
13-7	Measurement of Ground Resistance	362
13-8	Measurement of Soil Resistivity	365
13-9	Limitations on Ground-Electrode Design	368
13-10	Analytical and Experimental Studies of Electrodes	370
	Problems	371

chapter

14**POWER DISTRIBUTION 373**

14-1	General	373
14-2	Connection of Secondary to Primary Distribution	377
14-3	Transformers	382
14-4	Switching Devices	383
14-5	Conductors	384
14-6	Raceways	389
14-7	Motors	391
14-8	Grounding	394
	Problems	395

APPENDIX: TABLES FOR THE DETERMINATION OF CIRCUIT CONSTANTS 398

Table A-1	Resistivity and Temperature Coefficient of Conductor Materials	398
Table A-2	Characteristics of Copper Conductors	399
Table A-3	Characteristics of Aluminum Cable Steel Reinforced	401
Table A-4	Inductive Reactance Spacing Factor (x_d)	403
Table A-5	Shunt Capacitive Reactance Spacing Factor (x'_d)	404
Table A-6	Circuit Constants of Some Typical Cables (per conductor)	405
Table A-7	Typical Constants of Three-Phase Synchronous Machines	405
Table A-8	Transformer Reactance, Percent	406
Table A-9	Rotating Machine Reactances for Short-Circuit Calculation	407
Table A-10	Approximate Ampacities of Insulated Copper Cables According to Layout	407
Table A-11	Approximate Ampacities of Insulated Copper Cables According to Temperature	408

INDEX

chapter 1

The Electric Power System

1-1. REQUIREMENTS OF AN ELECTRIC SUPPLY SYSTEM

A great amount of effort is necessary to maintain an electric power supply within the requirements of the various types of customers served. Large investments are necessary, and continuing advancements in methods must be made as loads steadily increase from year to year. Some of the requirements for electric power supply are recognized by most consumers, such as proper voltage, availability of power on demand, reliability, and reasonable cost. Other characteristics, such as frequency, wave shape, and phase balance, are seldom recognized by the customer but are given constant attention by the utility power engineers.

The voltage of the power supply at the customer's service entrance must be held substantially constant. Variations in supply voltage are, from the consumer's view, detrimental in various respects. For example, below-normal voltage substantially reduces the light output from incandescent lamps. Above-normal voltage increases the light output but substantially reduces the life of the lamp. Motors operated at below-normal voltage draw abnormally high currents and may overheat, even when carrying no more than the rated horsepower load. Overvoltage on a motor may cause excessive heat loss in the iron of the motor, wasting energy and perhaps damaging the machine. Service voltages are usually specified by a nominal value and the voltage then maintained close to this value,

deviating perhaps less than 5 percent above or below the nominal value. For example, in a 120-volt residential supply circuit, the voltage might normally vary between the limits of 115 and 125 volts as customer load and system conditions change throughout the day.

Power must be available to the consumer in any amount that he may require from minute to minute. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric power company. As electrical energy cannot be stored (except to a limited extent in storage batteries), the changing loads impose severe demands on the control equipment of any electrical power system. The operating staff must continually study load patterns to predict in advance those major load changes that follow known schedules, such as the starting and shutting down of factories at prescribed hours each day.

The demands for reliability of service increase daily as our industrial and social environment becomes more complex. Modern industry is almost totally dependent on electric power for its operation. Homes and office buildings are lighted, heated, and ventilated by electric power. In some instances loss of electric power may even pose a threat to life itself. Electric power, like everything else that is man-made, can never be absolutely reliable. Occasional interruptions to service in limited areas will continue. Interruptions to large areas remain a possibility, although such occurrences may be very infrequent. Further interconnection of electric supply systems over wide areas; continuing development of reliable automated control systems and apparatus; provision of additional reserve facilities; and further effort in developing personnel to engineer, design, construct, maintain, and operate these facilities will continue to improve the reliability of the electric power supply.

The cost of electric power is a prime consideration in the design and operation of electric power systems. Although the cost of almost all commodities has risen steadily over the past many years, the cost per kilowatt-hour of electrical energy has actually declined. This decrease in cost has been possible because of improved efficiencies of the generating stations and distribution systems. Although franchises often grant the electric power company exclusive rights for the supply of electric power to an area, there is keen competition between electric power and other forms of energy, particularly for heating and for certain heavy-load industrial processes.

The power-supply requirements just discussed are all well known to most electric power users. There are, however, other specifications to the electric power supply which are so effectively handled by the power companies that consumers are seldom aware that such requirements are of importance.

The frequency of electric power supply in the United States is almost entirely 60 hertz (formerly cycles per second). The frequency of a system is

dependent entirely upon the speed at which the supply generator is rotated by its prime mover. Hence frequency control is basically a matter of speed control of the machines in the generating stations. Modern speed-control systems are very effective and hold frequency almost constant; deviations are seldom greater than 0.02 hertz.

In an ac system the voltage continually varies with time, at one instant being positive and a short time later being negative, going through 60 complete cycles of change in each second. Ideally a plot of the time change should be a sine wave, as shown in Fig. 1-1a. In poorly designed generating

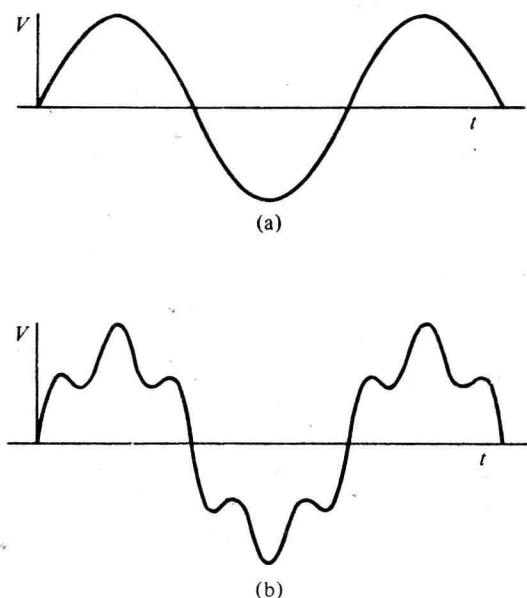


FIG. 1-1. (a) A voltage which varies sinusoidally with time. (b) A voltage wave shape which contains a fifth harmonic.

equipment, harmonics may be present and the wave shape may be somewhat as shown in Fig. 1-1b. The presence of harmonics produces unnecessary losses in the customer's equipment and sometimes produces hum in nearby telephone lines. The voltage wave shape is basically determined by the construction of the generation equipment. The power companies put specification limitations on the harmonic content of generator voltages and so require equipment manufacturers to design and build their machines to minimize trouble from this effect.

Practically all major power equipment is supplied by three-phase circuits. Three-phase circuits are essentially three single-phase circuits each of which has its own sine wave of voltage. If phase balance is perfect, each of

the three voltages is of the same magnitude but displaced in time from the other two by one third of a cycle. Modern three-phase generators are designed to have almost perfect phase balance, as shown in Fig. 1-2.

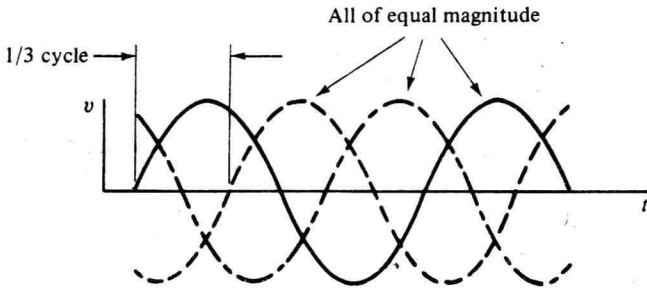


FIG. 1-2. The three voltage waves produced by a balanced three-phase generator.

Voltage unbalances produce unnecessary losses in three-phase motors and reduce the maximum starting torque. Few customers are aware of the problem of phase balance except in those rare instances where abnormal conditions are encountered.

Practically all consumers use the electric power supply to operate motors, transformers, and other devices in which iron is magnetized by currents from the electric power system. The currents that magnetize the iron do not influence the electric power bill (except where power-factor clauses apply) and so are seldom recognized by the customer. Nevertheless, provision must be made in the power system for supplying these magnetizing currents, and so their supply must be considered in specifying the characteristics of the generating, transmission, and distribution facilities that deliver power to the customer.

1-2. MINIMUM POWER SYSTEM

Electric power systems may be of great complexity and spread over large geographical areas. There is, however, a minimum system that can function as an electric power supply as shown in Fig. 1-3. The system consists of an energy source, a prime mover, a generator, and a load. Supervising it is some sort of a control system.

The *energy source* may be coal, gas, or oil burned in a furnace to heat water and generate steam in a boiler; it may be fissionable material which, in a nuclear reactor, will heat water to produce steam; it may be water in a pond at an elevation above the generating station; or it may be oil or gas burned in an internal combustion engine.

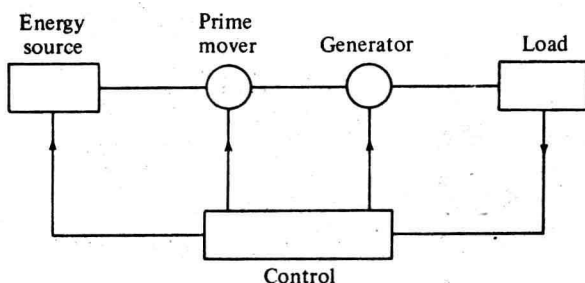


FIG. 1-3. The minimum electric power system.

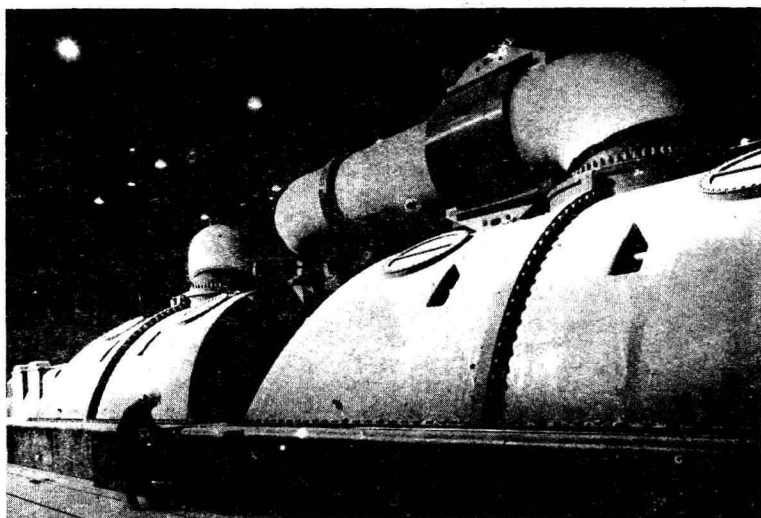


FIG. 1-4. A large steam turbine which drives a generator.

The *prime mover* may be a steam-driven turbine (Fig. 1-4), a hydraulic turbine or water wheel (Fig. 1-5), or an internal combustion engine (Fig. 1-6). Each one of these prime movers has the ability to convert energy in the form of heat, falling water, or fuel into rotation of a shaft, which in turn will drive the generator.

The *generator* may be an ac machine (or alternator) (Fig. 1-7), the type of machine that supplies most of the electric power used today. In special cases the generator may be a dc machine (Fig. 1-8).

The electrical *load* on the generator in Fig. 1-3 may be lights, motors, heaters, or other devices, alone or in combination. Probably the load will vary from minute to minute as different demands occur.

The *control system* functions to keep the speed of the machines sub-

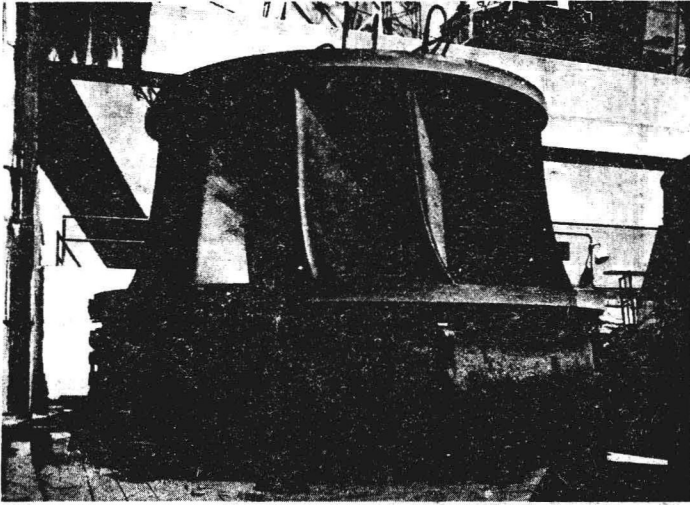


FIG. 1-5. The rotor of a 204,000 H.P. water wheel.

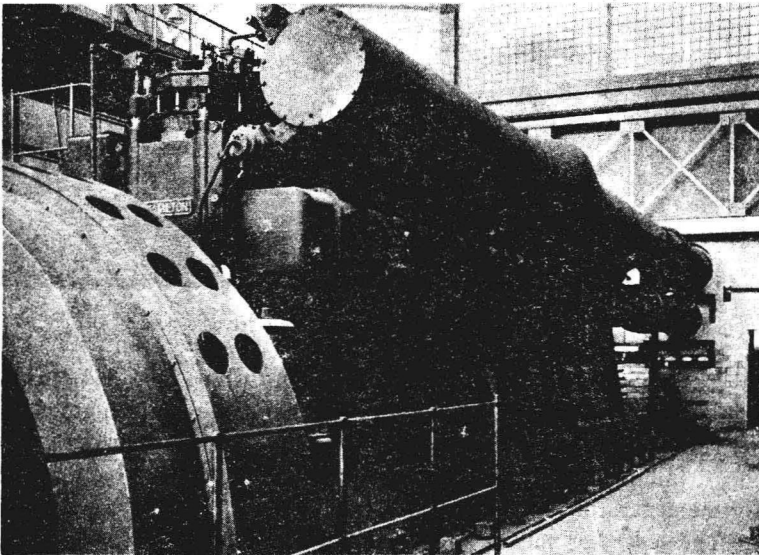


FIG. 1-6. A diesel engine.

stantially constant and the voltage within prescribed limits, even though the load may change. To meet these changing load conditions, it is necessary for fuel input to change, for the prime-mover input to vary, and for the torque on the shaft from the prime mover to the generator to change

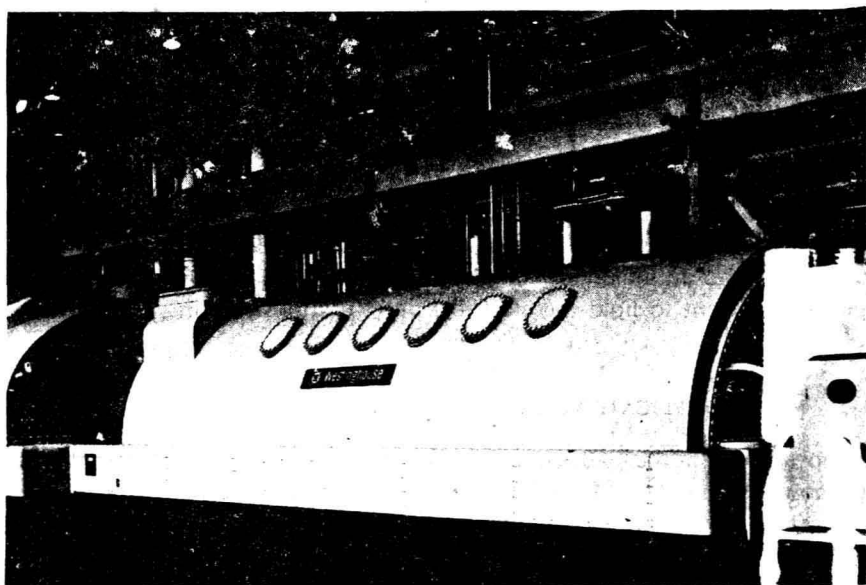


FIG. 1-7. An ac-generator rated 430,000 kVA, 24 kV, 3600 RPM.

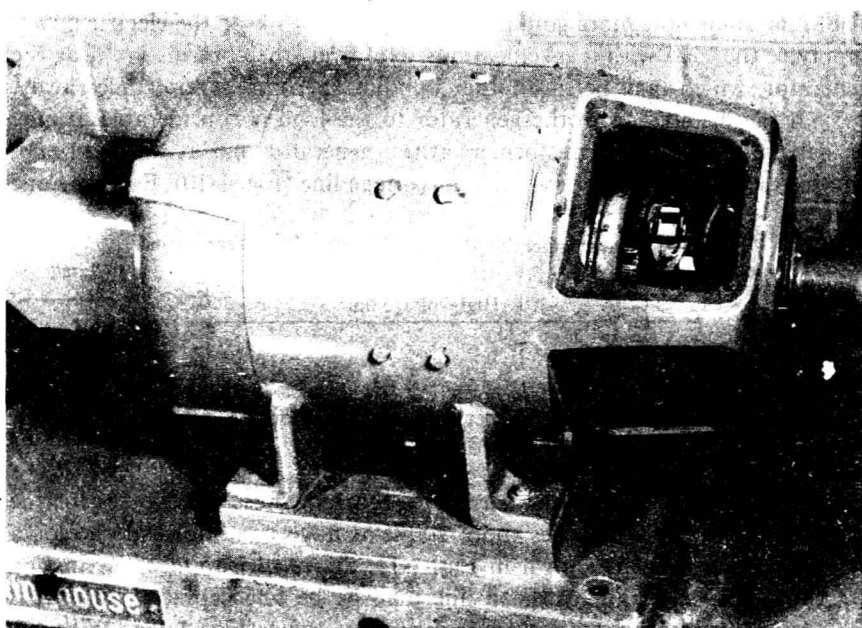


FIG. 1-8. A dc-generator rated 6 kW, 240 V, 1800 RPM.