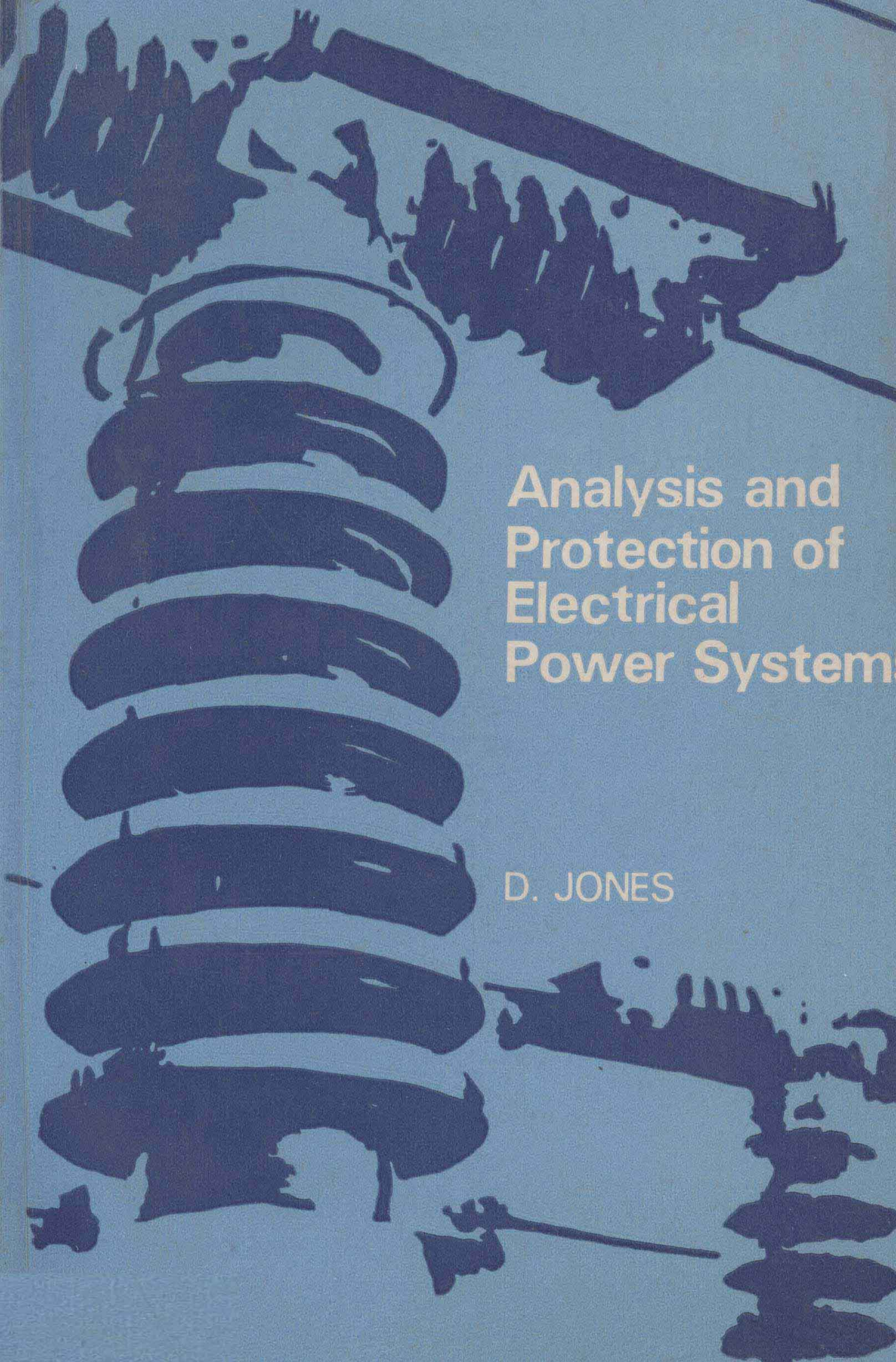

Analysis and Protection of Electrical Power Systems

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Preface

This book provides suitable material for an undergraduate course in the analysis and protection of power systems, and should prove helpful to students reading for degrees and diplomas in electrical power engineering. The subject is introduced by considering the basic requirements of a large electrical power system in respect of meeting the varying demands of the consumer from available energy sources. A discussion of the electrical characteristics of multiple-conductor systems is followed by a treatment of the performance characteristics of both a.c. and d.c. transmission systems. Because of their fundamental importance in power system analysis a complete chapter is devoted to the operation of synchronous machines and the stability problem. Another chapter deals with active and reactive power flow, in which the role of computers and other analytical tools is emphasized, the practical control problems encountered in power system operation also being discussed.

Since abnormal behaviour and possible faulty conditions form the *raison d'être* for the large capital investment in protective relaying, a whole chapter has been devoted to a discussion of the methods employed in fault analysis. In this respect a good grounding in symmetrical component methods is helpful in the understanding of power system fault performance; it is the author's opinion that such methods are amenable to a generalized analytical treatment. The use of digital computers for large-scale studies is illustrated, and fault analysis for protection purposes is considered in both symmetrical component and real co-ordinate terms.

Two complete chapters are concerned entirely with protective relaying. In these chapters the author has attempted to give the reader an insight into the fundamental problems of protective relaying, rather than a catalogue of protection schemes, and it is hoped that this more general approach will lead to a better understanding. A further chapter deals with system transient performance in which the relevance to protection is also discussed.

The treatment is analytical, and for this reason, descriptions of plant, which are freely available from the manufacturers, are omitted, except where necessary to improve understanding. Worked examples are included in the text, and exercises are provided for the student to tackle himself. Although written primarily for the undergraduate student, the young power systems engineer will find much of the material useful to him in understanding the theoretical aspects of his work.

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D.J.

Contents

Chapter 1

The Basic Requirements of a Large Electrical Power System

1.1 INTRODUCTION

The function of a large electrical power system is to connect bulk generating plant to the consumers' loads by means of an interconnected system of transmission and distribution networks. The needs of the consumer must be catered for as efficiently and economically as possible. Demands for both active and reactive power vary continuously. Such requirements must be met with sufficient reserve generation to supply any sudden increase in demand which could occur at any time.

The British grid system of electrical power transmission was originally formulated on what was termed the two-tier control system, whereby a national control centre co-ordinated the output of generating stations in various parts of the country, through a limited number of regional grid control centres. The Central Electricity Generating Board (C.E.G.B.) is responsible for the operation of about 230 power stations, the total generating capacity of which exceeds 38 000 MW. Over 700 grid substations transform and interconnect approximately 1 300, 6 500, 18 000 km (say 800, 4000 and 11 000 miles) respectively of 400, 275, and 132 kV overhead lines with about 2400 km (say 1 500 miles) of underground cable. The power stations themselves vary in age and size, and although some older stations have capacities of less than 100 MW, there are now stations of 2000 MW capacity coming into service, such stations having individual generating sets capable of generating 500 MW.

The Area Boards are responsible for distribution usually at 33 kV and below, although some Boards have 132 kV feeders for providing a unidirectional feed. The Boards are obliged by statutory regulations to supply the consumer at a voltage within ±6% of the declared value and are directly concerned with consumer service.

1.2 CONSUMER NEEDS

Sufficient operational experience has now been acquired to predict feasibly the daily demand, which varies with the season of the year, the day of the week and the time of day. Curves illustrating the

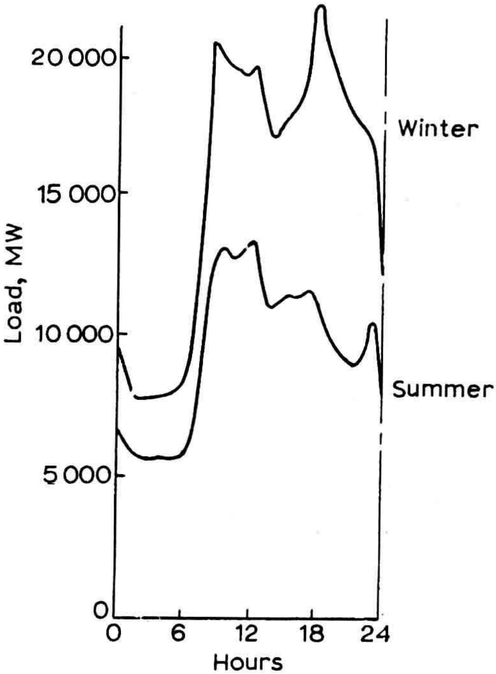

Fig 1.1 Variation in power consumption during a typical working day

variations in demand during a typical working day for both summer and winter conditions are given in Fig 1.1. The way in which computers may assist such predictions is discussed in Chapter 5.

1.3 ENERGY RESOURCES

The main sources of energy currently being utilized in the United Kingdom for electrical power production are coal, nuclear reactors, oil and water power. Approximately 56×10^9 kg (say 55×10^6 tons) of coal are burned each year in conventional power stations. The consumption of oil in terms of coal equivalent is some 5% of this value. At the moment nuclear generation accounts for only about 5% coal equivalent, but this figure will increase as new nuclear power stations are built. In this country the combined outputs of hydro, pumped-storage and gas-turbine generating stations account for only about 3% of the total coal equivalent generation.

It is usually advantageous to site coal-fired stations near the coalfields. Hydro and pumped-storage power stations must be sited where there is the available abundance and head of water. In the past it has been a statutory requirement that nuclear stations must be sited well away from large towns and cities, but in future such stringency is likely to be slowly relaxed. Gas-turbine generation is of comparatively low output capacity and tends to be utilized by Area Boards for "peak-lopping" purposes.

1.3.1 Coal-fired Generating Stations

Before selecting a site for a coal-fired power station its accessibility is a major consideration. The facilities for fuel supply, whether by road, rail or canal, and arrangements for coal storage must be adequate. Ample water supply must be available for cooling and other station services, while facilities must be provided for disposal of the vast quantities of ash produced.

Assuming such a site is available, the overall station capacity must be considered in terms of the number and ratings of individual sets. The steam conditions of the prime movers (operating temperatures and pressures), the generating voltage and cooling arrangements must be stipulated. Boiler capacities, their method of firing and control must be decided on. Furthermore such features as feed-water heating and make-up, steam reheating, ash handling and grit arrestors are all important considerations. Other electrical equipment such as generator-transformers, main switchgear and station auxiliaries will be required, and a control room must be incorporated.

It is interesting to note the following figures in respect of a typical 2000 MW coal-fired station. Such a station comprises four turbo-generators each of 500 MW capacity. Each set is supplied by its own boiler with an evaporative capacity of about $1{\cdot}6 \times 10^6$ kg (say $3{\cdot}5 \times 10^6$ lb of steam per hour. The steam conditions at the turbine stop-valve would be of the order of $16 \times 10^6 \text{N/m}^2$ and 540°C (say 2500 lb/in^2 and 1000°F). Such a station would burn about 5×10^9 kg (say 5×10^6 tons) of coal per annum.

Most boiler plants incorporate such added refinements as a super-heater, economizer and air pre-heating arrangement. Modern coal-burning boilers are either of the pulverized-fuel or the stoker type (chain grate, etc.). Coal storage facilities are usually provided for about seven weeks of winter supply. Condenser cooling water requirements are about 2000 litres (say 50 gal) per kilowatt-hour. Other station services such as ash quenching, boiler make-up and bearing cooling could add a further 5% to the preceding requirement.

The tendency nowadays has been to standardize generating voltages within the range 11–15 kV in order to enable standard transformers to be used to build up the transmission voltages. The generator and its associated transformer are coupled electrically as a single unit. The performance of generators and transformers is discussed in Chapters 4 and 6 respectively, while the protection of such units receives attention in Chapter 7.

Many modern alternators employ hydrogen cooling, though some of the very large sets are water cooled. Because of its reduced density and higher thermal conductivity the heat transfer coefficient for hydrogen cooling is about twice that of air for a given frame size. By utilizing pressures of the order 10^5 N/m^2 (say 15 lb/in^2), it has been possible to increase outputs considerably without much increase in physical size. Usually the hydrogen is circulated by radial vanes on the rotor and cooled by water coolers mounted on the stator frame.

1.3.2 Nuclear-powered Generating Stations

Uranium has three isotopes which occur naturally in percentages of 0·06, 0·7 and 99·24% and are known as U^{234}, U^{235} and U^{238} respectively. The isotope U^{235} is particularly fissionable, hence its use in nuclear reactors. Nuclear fission may be described as a process in which a free neutron bombards the nucleus, causing a break-up and release of other neutrons and energy in the form of heat. Collision of the released neutrons with other nuclei causes further fission, and a chain reaction is set up. Neutrons emerge speedily, which diminishes their chances of hitting other nuclei. Use is therefore made in British reactors of a graphite moderator which slows down the neutrons without absorbing them. The uranium fuel rods are encased in magnesium cans, to retain the radioactive products of fission. In addition, these cans protect the uranium from corrosion and also assist with heat transfer. It is usual to support each element in a graphite sleeve, the whole unit being inserted into a hole or channel in the graphite moderator. The moderator may house about 4000 such channels.

The chain reaction is started by bringing together natural uranium of a critical amount in a graphite moderator. Control of the reaction is by means of boron rods, which when inserted into the reactor absorb neutrons. When the control rods are so positioned that power is neither increasing nor decreasing the reactor is said to be critical. Owing to the escape of neutrons from the moderator, there is a minimum limit to the size of the reactor called the critical size.

The main difference between the British nuclear power stations and their conventional counterparts is simply the fact that heat is produced for steam raising from a nuclear reaction instead of by the combustion of fuel. The initial nuclear power programme in the United Kingdom produced the gas-cooled reactors. Improvements in design have led to the advanced gas-cooled reactors (A.G.R.). In this respect policy has differed somewhat from that of the Americans, who have persevered with boiling-water reactors (B.W.R.) and pressurized-water reactors (P.W.R.).

As previously stated, the British reactors use graphite as the moderator and generation of heat takes place within the reactor core itself, this core being a large cylindrical or spherical structure with a large number of channels running vertically. In the first generation of reactors such a core of the cylindrical-reactor type would be typically about 7·5m (say 24ft) high and about 15m (say 49ft) in diameter. Over 4000 channels may be used, and heat transfer is by means of carbon dioxide gas. The gas is blown through the moderator holes at a high pressure, $128 \times 10^4 N/m^2$ (say $185 lb/in^2$), and the heat of fission is transferred from the uranium through the cans to the gas. The hot gas is then blown into the heat exchanger vessels (boilers), where the water is turned into steam for driving conventional turbo-alternators.

The principles adopted by the Americans in the B.W.R. and P.W.R. arrangements are somewhat different from the foregoing. The B.W.R. has its reactor core surrounded by water, which is in a pressure vessel under a high pressure of the order of $7 \times 10^6 N/m^2$ (say $1000 lb/in^2$). The boiling water so produced raises steam for direct feeding into the turbines, whence the steam passes to a condenser in the usual way. Shielding of the turbines is necessary because of radioactivity, which is transferred by the steam passing through the reactor core. The P.W.R. type employs a reactor core which is surrounded by heavy water and is housed in a pressure vessel subjected to a pressure of approximately twice that of the B.W.R. The heavy water acts as a coolant and is used for steam raising in heat exchangers. A complete discourse on nuclear reactors generally is beyond the scope of the text, but reference to the literature [1, 2, 3, 4, 5] quoted at the end of this chapter will provide a good background to the subject.

With respect to the first generation of British gas-cooled reactor power stations, it will be appreciated that it is necessary to operate the blower system at a high pressure in order to obtain the required heat power transfer with a reasonably low expenditure of blower power. Even so, the blower motors absorb well over 10% of the station's power. In a typical 500 MW gas-cooled nuclear station the blower motors would be supplied from two auxiliary 33 MW variable-frequency turbo-alternator sets, a similar third set being utilized as a stand-by.

Some earlier stations used steel pressure vessels, which necessitated welding on site to Class I standard. Such pressure vessels were surrounded by a 2·7 m (say 9 ft) thick biological shield of concrete to safeguard personnel. Pressure vessels are no longer made of steel, use being made of prestressed concrete instead. Refuelling may be carried out on load using a special charge/discharge machine housed on top of the pressure vessel. The fuel elements are lowered through stand-pipes with shielding plugs and stepped diameters to minimize radiation. The steam-raising units are also pressure vessels and are symmetrically situated around the reactor as illustrated by the simple sketch of Fig 1.2. Usually about six heat exchangers are used per reactor. Large-diameter ducts connect with the reactor and form closed circuits for circulating the gas coolant. The heat exchangers would normally be about 27·2 m high (say 89 ft), 6 m (say 20 ft) in diameter and made of 65 mm (say $2\frac{1}{2}$ in) thick welded steel.

In a typical 500 MW gas-cooled nuclear station each of six heat exchangers would produce about $0{\cdot}22 \times 10^6$ kg (say 500000 lb) of steam per hour at two pressures, $450 \times 10^4\,N/m^2$ and $130 \times 10^4\,N/m^2$ at a temperature of nearly 370°C (say 650 lb/in² and 185 lb/in² at 700°F). Steam dumping condensers are normally required because a reactor may still produce about 5% of its full-load heat when shut down. Specially designed handling equipment must be provided to deal with the spent fuel discharged from the reactors. The spent fuel is stored for several months in a cooling pond to allow the high-intensity radiation to die down, after which it is transported for processing in the Atomic Energy Authority's factories.

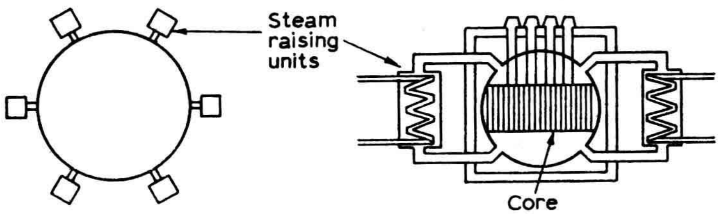

FIG 1.2 Basic arrangement of steam-raising units of nuclear reactor

1.3.3 Hydro-electric Power Stations

The main consideration in selecting a site is the amount of available energy in a particular fall of water. Such installations tend to be classified in accordance with the head available and the required storage time. They may have a mere 15 m (say 50 ft) head, taking less than 2 hours storage time, or have a very high head which could require several hundred hours to fill the reservoir. The type of turbine used varies with the available head. Kaplan turbines of the axial-flow propellor type are used for low heads. Pelton bucket-wheel turbines are used when the head is about 300 m (say 1000 ft) or more. Francis turbines in which the driving wheel rests inside a spiral casing tend to be used for medium heads of about 100 m (say 330 ft). The generators are normally of the salient-pole type and run at much lower speeds than turbo-alternators. Because of the vertical axis of the rotating plant, the thrust bearing is an important feature. Surge tanks must be provided to give a by-pass when water is not required for driving the turbine, while arrangements must be made for the diffusion of spent water to prevent erosion.

1.3.4 Pumped Storage Stations

These simply comprise upper and lower reservoirs, with facilities for pumping from lower to upper and discharging from upper to lower. The efficiency is of the order of 60–70%, so that the cost of providing such energy is about 1·6 times the cost of pumping. The most economical time for pumping is at night when there is plenty of spare high-merit generation available.

1.3.5 Integration of Steam and Hydro Plant

In the United Kingdom, catchment areas are small, rainfall is erratic and storage expensive. Since the demand is such that a certain low *load factor* (ratio of average load to peak load) is useful, hydro schemes are designed to meet this requirement. A hydro station output would be fitted into the generating programme in accordance with the number of hours at full output such a station might provide each day. This would be determined by the storage, the current rainfall and the expected rainfall.

1.3.6 The Use of Non-rotating Generators

Some interesting work has been carried out during the past few years in order to develop certain methods of direct generation at a reasonably high power level. Much publicity [6] has been given to

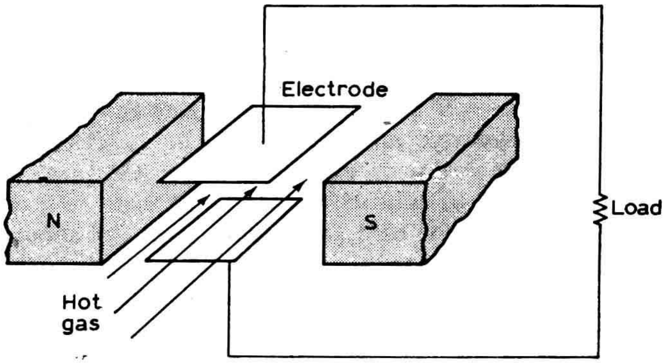

FIG 1.3 Elementary m.h.d. generator

magneto-hydrodynamic generation (M.H.D.). Such generators operate on the principle of passing hot gases, obtained from the combustion of fuel oil, between the poles of an electromagnet having a magnetic field of high density. By seeding the gas with potassium, its conductivity is improved, and the arrangement therefore constitutes