Modern Power System Analysis

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MODERN POWER SYSTEM ANALYSIS

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Preface

Mathematical modelling and solution on digital computers is the only practical approach to systems analysis and planning studies for a modern-day power system with its large size, complex and integrated nature. The stage has, therefore, been reached where an undergraduate must be trained in the latest techniques of analysis of large-scale power systems. A similar need also exists in the industry where a practicing power system engineer is constantly faced with the challenge of the rapidly advancing field. This book has been designed to fulfil this need by integrating the basic principles of power system analysis illustrated through the simplest system structure with analysis techniques for practical size systems. In this book large-scale system analysis follows as a natural extension of the basic principles. The form and level of some of the well-known techniques are presented in such a manner that undergraduates can easily grasp and appreciate them.

The book is designed for a two-semester course at the undergraduate level. With a judicious choice of advanced topics, some institutions may also find it useful for a first course for postgraduates.

The reader is expected to have a prior grounding in circuit theory and electrical machines. He should also have been exposed to Laplace transform, linear differential equations, optimization techniques and a first course in control theory. Matrix analysis is applied throughout the book. However, a knowledge of simple matrix operations would suffice and these are summarised in an appendix for quick reference.

The digital computer being an indispensable tool for power system analysis, computational algorithms for various system studies such as load flow, fault level analysis, stability, etc. have been included at appropriate places in the book. It is suggested that where computer facilities exist, students should be encouraged to build computer programmes for these studies using the algorithms provided. Further, the students can be asked to pool the various programmes for more advanced and sophisticated studies, e.g. optimal scheduling. An important novel feature of the book is the inclusion of the latest and practically useful topics like unit commitment, generation reliability, optimal thermal scheduling, optimal hydro-thermal scheduling and decoupled load flow in a text which is primarily meant for undergraduates.

The introductory chapter contains a discussion on various methods of electrical energy generation and their techno-economic comparison. A glimpse is given into the future of electrical energy. The reader is also exposed to the Indian power scenario with facts and figures.

Chapters 2 and 3 give the transmission line parameters and these are included for the sake of completeness of the text. Chapter 4 on the representation of power system components gives the steady state models of the synchronous machine and the circuit models of composite power systems along with the per unit method.

Chapter 5 deals with the performance of transmission lines. The load flow problem is introduced right at this stage through the simple two-bus system and basic concepts of watt and var control are illustrated. A brief treatment of circle diagrams is included as this forms an excellent teaching aid for putting across the concept of load flow and line compensation. *ABCD* constants are generally well covered in the circuit theory course and are, therefore, relegated to an appendix.

Chapter 6 gives power network modelling and load flow analysis, while Chapter 7 gives optimal system operation with both approximate and rigorous treatment.

Chapter 8 deals with load frequency control wherein both conventional and modern control approaches have been adopted for analysis and design. Voltage control is briefly discussed.

Chapters 9–11 discuss fault studies (abnormal system operation). The synchronous machine model for transient studies is heuristically introduced to the reader.

Chapter 12 emphasises the concepts of various types of stability in a power system. In particular the concept of transient stability is well illustrated through the equal area criterion. The classical numerical solution technique of the swing equation as well as the algorithm for large system stability are advanced.

Every concept and technique presented is well supported through examples employing mainly a two-bus structure while sometimes three- and four-bus illustrations wherever necessary have also been used. A large number of unsolved problems with their answers are included at the end of each chapter. These have been so selected that apart from providing a drill they help the reader to develop a deeper insight and illustrate some points beyond what is directly covered by the text.

The internal organisation of various chapters is flexible and permits the teacher to adapt them to the particular needs of the class and curriculum. If desired, some of the advanced level topics could be bypassed without loss of continuity. The style of writing is specially adapted to self-study. Exploiting this fact a teacher will have enough time at his disposal to extend the coverage of this book to suit his particular syllabus and to include tutorial work on the numerous examples suggested in the text.

The authors are indebted to their colleagues at the Birla Institute of Technology and Science, Pilani and the Indian Institute of Technology, Delhi for the encouragement and various useful suggestions they received from them while writing this book. They are grateful to the authorities of the Birla Institute of Technology and Science, Pilani and the Indian Institute of Technology, Delhi for providing facilities necessary for writing the book. The authors welcome any constructive criticism of the book and will be grateful for any appraisal by the readers.

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Contents

1 Introduction

1.1 A PERSPECTIVE

Electrical energy is an essential ingredient for the industrial and all-round development of any country. It is a coveted form of energy, because it can be generated centrally in bulk and transmitted economically over long distances. Further, it can be adapted easily and efficiently to domestic and industrial applications, particularly for lighting purposes and for mechanical work[1], e.g. drives. The per capita consumption of electrical energy is a reliable indicator of a country's state of development—figures for 1970 are 111 kWh for India and 14,635 kWh for Norway.

Conventionally electrical energy is obtained by conversion from fossil fuels (coal, oil, natural gas), the nuclear and hydro sources. Heat energy released by burning fossil fuels or by fission of nuclear material is converted to electricity by first converting heat energy to the mechanical form through a thermocycle, and then converting mechanical energy through generators to the electrical form. Thermocycle is basically a low efficiency process—highest efficiencies for modern large size plants range up to 45%, while smaller plants may have considerably lower efficiencies. The earth has fixed non-replenishable resources of fossil fuels and nuclear materials, with certain countries overendowed by nature and others deficient. Hydro energy, though replenishable, is also limited in terms of power. The world's increasing power requirements can only be partially met by hydro sources. Furthermore, ecological and biological factors place a stringent limit on the use of hydro sources for power production. (The USA has already developed around 50% of its hydro potential; and hardly any further expansion is planned because of ecological considerations.)

With the ever increasing per capita energy consumption and exponen-

[1]Electricity is a very inefficient agent for heating purposes, because it is generated by the low efficiency thermocycle from heat energy. Electricity is used for heating purposes only for very special applications, say an electric arc furnace.

tially rising population, technologists already see the end of the earth's non-replenishable fuel resources[2]. The recent oil crisis has dramatically drawn attention to this fact. In fact, we can no longer afford to use oil as a fuel for generation of electricity. In terms of bulk electrical energy generation a distinct shift is taking place across the world in favour of coal and in particular nuclear sources for generation of electricity. Also the problems of air and thermal pollution caused by power generation have to be efficiently tackled to avoid ecological disasters. A coordinated worldwide action plan is, therefore, necessary to ensure that energy supply to humanity at large is assured for a long time and at a low economic cost. Some of the factors to be considered and actions to be taken are:

1. *Curtailment of energy consumption*: The energy consumption of most developed countries has already reached a level, which this planet cannot afford. There is, in fact, a need to find ways and means of reducing this level. The developing countries, on the other hand, have to intensify their efforts to raise their level of energy production to provide basic amenities to their teeming millions. Of course, in doing so they need to constantly draw upon the experiences of the developed countries and guard against obsolete technology.

2. *Intensification of efforts to develop alternative sources of energy including unconventional sources like solar, tidal energy, etc.*: Distant hopes are pitched on fusion energy, but the scientific and technological advances have yet a long way to go in this regard. Fusion when harnessed could provide an inexhaustible source of energy. A breakthrough in the conversion from solar to electric energy could provide another answer to the world's steeply rising energy needs.

3. *Recycling of nuclear wastes*: Fast breeder reactor technology is expected to provide the answer for extending nuclear energy resources to last much longer.

4. *Development and application of antipollution technologies*: In this regard the developing countries already have the example of the developed countries before them whereby they can avoid going through the phases of intense pollution in their programmes of energy development. Bulk power generating stations are more easily amenable to control of pollution since centralized one-point measures can be adopted.

Electrical energy today constitutes about 15–20% of the total annual energy consumption on a worldwide basis. This figure is expected to rise

[2]Varying estimates have been put forth for reserves of oil, gas and coal, and fissionable materials. At the projected consumption rates, oil and gases are not expected to last much beyond 70 years; several countries will face serious shortages of coal after A.D. 2200; while fissionable materials may carry us well beyond the middle of the next century. These estimates, of course, cannot be regarded as highly dependable.

in favour of electrical energy as oil supply for industrial uses becomes more stringent. Transportation can be expected to go electric in a big way in the long run, when non-conventional energy resources are well developed or a breakthrough in fusion is achieved.

To understand some of the problems that the power industry will have to face in the last two decades of this century, let us briefly review some of the characteristic features of generation and transmission. Electricity, unlike water and gas, cannot be stored economically (except in very small quantities—in batteries), and also the electric utility can exercise little control over the load (power demand) at any time. The power system must, therefore, be capable of matching the output from generators to the demand at any time at a specified voltage and frequency. The difficulty encountered in this task can be imagined from the fact that load variations over a day comprise three components—a steady component known as *base load*; a varying component whose daily pattern depends upon the time of day, weather, season, a popular festival, etc.; and a purely randomly varying component of relatively small amplitude. Figure 1.1 shows a typical daily load curve. The characteristics of a daily load curve on a gross basis are indicated by peak load and the time of its occurrence and *load factor* defined as

$$\frac{\text{average load}}{\text{maximum (peak) load}} = \text{less than unity}$$

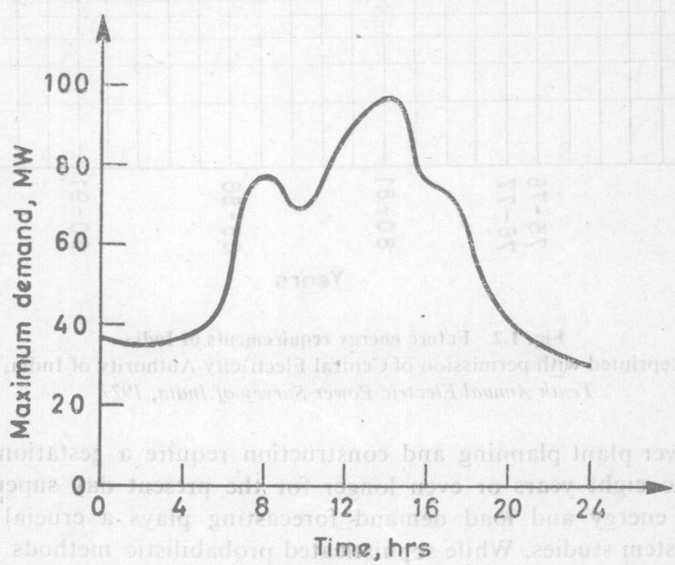

Fig. 1.1 Typical daily load curve

The average load determines the energy consumption over the day, while the peak load along with considerations of standby capacity determines the plant capacity for meeting the load.

A high load factor helps in drawing more energy from a given installation. As individual load centres have their own characteristics, their peaks in general have a time diversity, which when utilized through transmission interconnection, greatly aids in jacking up load factors at an individual plant—excess power of a plant during light load periods is evacuated through long distance high voltage transmission lines, while a heavily loaded plant receives power.

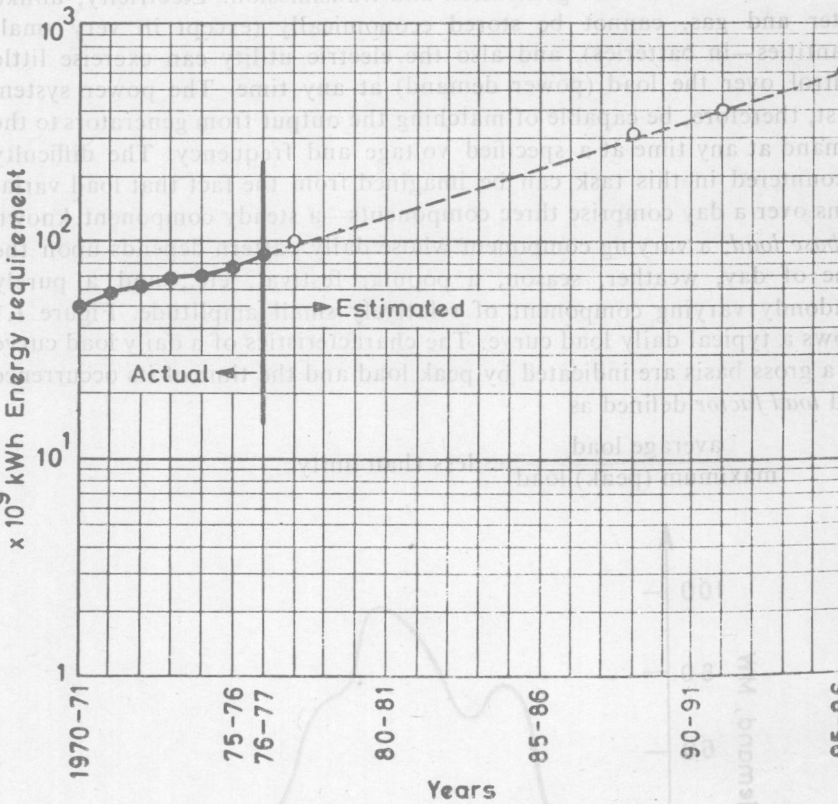

Fig. 1.2 Future energy requirements of India
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As power plant planning and construction require a gestation period of four to eight years or even longer for the present day super power stations, energy and load demand forecasting plays a crucial role in power system studies. While sophisticated probabilistic methods exist in literature [38], the simple extrapolation technique is quite adequate for long range forecasting. Figure 1.2 shows the energy demand and Fig. 1.3 shows the installed generating capacity in India, plotted on semilog scale versus linear time scale. These plots (shown by solid lines) are straight lines indicating that the electrical energy requirement is an exponential growth function (so is population growth—a truly formidable combination). As per the slope of these plots, the continuous increase in power demand[3] has been roughly doubling every ten years. This applies to most countries, although in some developing countries it is even higher. The straight line plots can be easily extrapolated (shown dotted) to predict the power demand[4] in the year 1995. As per Fig. 1.3 the installed generating capacity in India must rise from 29×10^3 MW in 1979 to 140×10^3 MW in 1995—a stupendous task indeed. This, in turn, would require a corresponding development in coal resources.

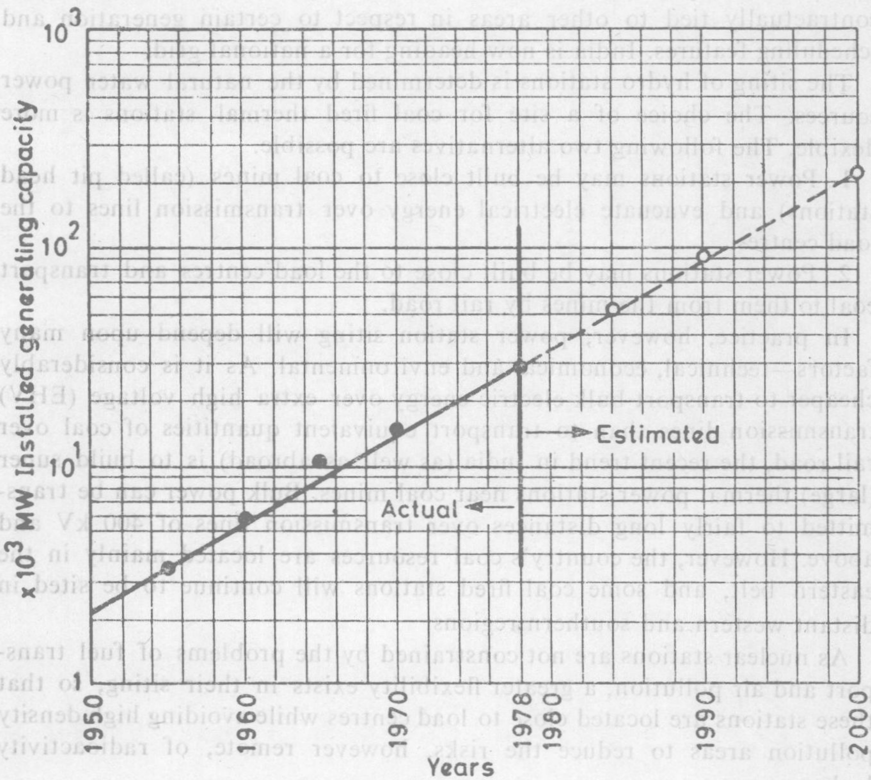

Fig. 1.3 Growth of Indian electrical power demand
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1.2 STRUCTURE OF POWER SYSTEMS

Generating stations, transmission lines and the distribution systems are the main components of an electric power system. Generating stations and a distribution system are connected through transmission lines,

[3]Two-thirds of the total power required in India is for industrial consumption.
[4]As per Kirit Parikh [29], generation of electricity in India will have to be around 700 billion kWh in A.D. 2000–2001 compared to less than 50 billion kWh in 1970–71.

which also connect one power system (grid, area) to another. A distribution system connects all the loads in a particular area to the transmission lines.

For economical and technological reasons (which will be discussed in detail in later chapters), individual power systems are organized in the form of electrically connected areas or regional grids (also called power pools). Each area or regional grid operates technically and economically independently, but these are eventually interconnected[5] to form a national grid (which may even form an international grid) so that each area is contractually tied to other areas in respect to certain generation and scheduling features. India is now heading for a national grid.

The siting of hydro stations is determined by the natural water power sources. The choice of a site for coal fired thermal stations is more flexible. The following two alternatives are possible.

1. Power stations may be built close to coal mines (called pit head stations) and evacuate electrical energy over transmission lines to the load centres.

2. Power stations may be built close to the load centres and transport coal to them from the mines by rail road.

In practice, however, power station siting will depend upon many factors—technical, economical and environmental. As it is considerably cheaper to transport bulk electric energy over extra high voltage (EHV) transmission lines than to transport equivalent quantities of coal over rail road, the recent trend in India (as well as abroad) is to build super (large) thermal power stations near coal mines. Bulk power can be transmitted to fairly long distances over transmission lines of 400 kV and above. However, the country's coal resources are located mainly in the eastern belt, and some coal fired stations will continue to be sited in distant western and southern regions.

As nuclear stations are not constrained by the problems of fuel transport and air pollution, a greater flexibility exists in their siting, so that these stations are located close to load centres while avoiding high density pollution areas to reduce the risks, however remote, of radioactivity leakage.

In India, as of now, about 60% of electrical power used is generated in thermal plants (including nuclear). The remaining 40% comes from hydro stations. Coal is the fuel for most of the steam plants; the remainder depend upon fuel oil and nuclear fuels. After the hike in oil prices in

[5]Interconnection has the economic advantage of reducing the reserve generation capacity in each area. Under conditions of sudden increase in load or loss of generation in one area, it is immediately possible to borrow power from adjoining interconnected areas. Interconnection causes larger currents to flow on transmission lines under faulty condition with a consequent increase in capacity of circuit breakers. Also, the synchronous machines of all interconnected areas must operate stably and in a synchronized manner. The disturbance caused by a short circuit in one area must be rapidly disconnected by circuit breaker openings before it can seriously affect adjoining areas.