Power System Operation

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Consulting Engineer

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Power System Operation

Energy control center of a large power system (Pacific Gas and Electric Company).
NOTE: ***Control console center left with EHV dynamic board, and computer equipment in background beyond glass partition.***

To Power System Dispatchers

Preface

This book was originally produced in 1970, under the auspices of the Western Systems Coordinating Council, primarily to provide power system operators with material useful in power system operation, including information on interconnection. Apparently it did fill a need, at least to some extent, as it has received much greater acceptance than was originally anticipated, both domestically and in foreign countries.

Because of the many advances in control technology and system protection, and the changes in fuel costs for power generation, some sections of the first edition were in need of revision and expansion to bring the text up to date. It is for these reasons that this new edition has been prepared.

There has been no change in intent, however. The objective is still to provide, in as simple terms as possible, a description of the functioning of power systems and their control. As in the first edition, the use of advanced mathematics has been avoided, and appendix sections have included the development of the required mathematics in sufficient detail to meet the requirements of the readers.

It is sincerely hoped that the material presented in this book will be of value to power system operators, and that it will enable them to better understand the behavior of power systems under both normal and abnormal conditions.

The revised text has been reviewed by Robert F. Wolff of *Electrical World* and Sheldon Strauss of *Power Magazine*. Thanks are also due to Peggy Lamb of McGraw-Hill for her suggestions on construction and arrangement, and to Diane Heiberg, who has had the responsibility of editing the book.

R. H. MILLER

Preface to the First Edition

This book has been prepared under the auspices of the Western Systems Coordinating Council in an effort to provide material that would be useful to power system dispatchers in better understanding the principles of electric power system operation. To the extent possible the use of mathematics has been avoided. Where mathematics has been required, appendix sections have been included to develop the basis for the mathematical applications.

A considerable portion of the manual has been devoted to power system control, economics, and interconnected operation. Although these topics are well understood by engineers, there is little information conveniently available for power system operators not having formal engineering training.

Procedural information for clearing lines and equipment has been purposely avoided since practices on individual power systems vary and it is believed that such procedures can best be developed by the systems or by mutual agreement for interconnected operation.

The manual has been reviewed by various representatives of the Western Systems Coordinating Council and their helpful suggestions are appreciated. Particular thanks are due Mr. William Bosshart of the Bonneville Power Administration, Mr. Clyde Reikofski of the United States Bureau of Reclamation, and Mr. K. K. Dols of the Northern States Power Company for their detailed reviews of the material in the manual and their suggestions and constructive criticisms of the text material, and Mr. Harry McMasters of the Pacific Gas and Electric Company for his careful reading and editorial suggestions. Thanks are also due Mrs. Lorrette Hopson and Mrs. Esperanza Martinez of the Pacific Gas and Electric Company for their patience in typing the drafts of the manuscript.

R. H. MILLER

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Introduction

Although the basic principles of power system operation do not change, there have been significant developments in the tools available to power system operators since the first edition of this book was issued in 1970. Consequently, it seems appropriate to provide at least some discussion of these tools and their applications.

The basic purpose of the book has not changed—that is, to discuss in relatively simple terms how power systems operate and some of the problems that power system operators meet in their day-to-day operations. In general, the book attempts to consider system behavior and the effects of operations on a system rather than the functioning of specific types of power system equipment.

Because of the wide acceptance and application of supervisory control and data acquisition (SCADA) systems, a new chapter has been added describing such systems and some of their applications.

The section on power system protection has also been somewhat expanded to include directional-comparison and transfer trip relaying systems.

Other minor changes in the text and its arrangement have been made, in the hope that it will be more logical and an improvement over the original edition.

The discussions of the various items in the book are necessarily brief, as the intention has been to produce not a detailed textbook, but rather a ready source of at least some information on topics of interest to power system operators.

1

Basic Principles

Before the factors affecting the behavior of power systems are discussed, some basic electric circuit theory will be presented, since the behavior of all electric circuits and machinery is affected by the electrical components making up the circuits. A knowledge of these fundamental concepts is essential before power system behavior can be understood. All electric circuits contain resistance, inductance, and capacitance. The combination and proportion of these elements in a circuit determine the behavior of the circuit.

RESISTANCE

Resistance can be defined as the element of an electric circuit that limits the flow of current in the electric circuit. Electric energy flowing in a circuit containing resistance is converted to heat energy proportional to the square of the current. The energy consumed in a circuit containing resistance is equal to $(\text{amperes})^2 \times$ resistance (ohms) watts, or power consumed $= I^2R$ watts. The behavior of a circuit containing only resis-

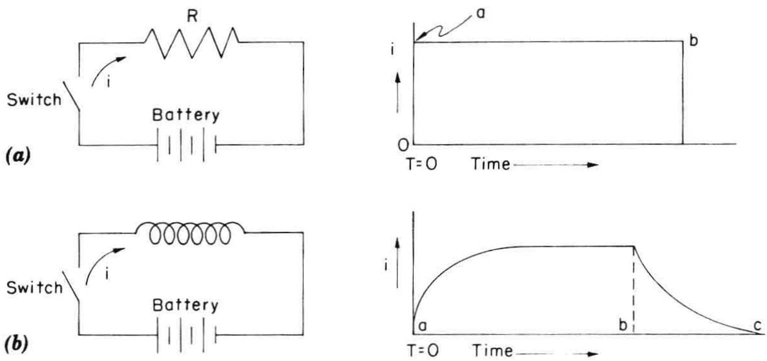

figure 1-1 Effects of resistance and inductance on change of flow of current. (*a*) In a circuit containing only resistance, when the switch is closed at $T = 0$, current rises instantaneously to its final value i at point a, and when the switch is opened at time b, it decreases immediately to zero. (*b*) In a circuit containing inductance, when the switch is closed at a ($T = 0$), current rises over a period of time until it reaches a final value i determined by the resistance and inductance in the circuit. When the switch is opened at time b, the current decays to zero over a period of time, again determined by the resistance and inductance in the circuit.

tance is shown in Fig. 1-1*a*. The amount of resistance in a circuit is affected by the resistivity of the material conducting a current. It varies inversely with the cross-sectional area of the material and directly with its length. Most metals are relatively good conductors of electricity; that is, they have a low resistivity. Other materials, such as wood, glass, or rubber, have a very high resistivity and are classified as insulators. Liquids and gases may have high or low resistivity, depending on temperature and various other factors.

INDUCTANCE

Inductance can be defined as the element of an electric circuit which opposes sudden increases or decreases of current flowing in the circuit. Inductance stores energy in a magnetic field when current is increased and delivers energy back to the circuit when current is decreased. The amount of energy returned to a circuit would exactly equal the amount of energy stored if there were no resistance losses.

The effect of inductance in a circuit is to delay current changes. Figure 1-1 shows the effect of resistance and inductance in a circuit.

After the initial closing of the switch, the current increases exponentially to a maximum, limited by the resistance in the circuit, and will maintain this value until the switch is opened, when it will begin to decrease exponentially. In an ac circuit the voltage is continuously changing. Consequently, the current will also change, but at a time somewhat delayed, because, as noted above, an inductance opposes a sudden change in current. As a result, the current in a circuit containing inductance is said to "lag" the voltage. One complete cycle is 360 electrical degrees, and in a circuit with pure inductance the current will lag the voltage by 90 degrees. Practical circuits always contain some resistance, so that in such a circuit the current will lag the voltage, but at an angle of less than 90 degrees, depending on the ratio of resistance to inductive reactance.

Coils of a conductor are primarily inductive but always contain some resistance. The amount of inductance is proportional to the number of turns and to the material used in the core. Magnetic materials such as iron greatly increase the inductance of a coil as compared with an air-core coil. Straight conductors, such as transmission lines, also have inductance proportional to the length of the line and the size and spacing of the conductors. This factor is very important in determining the behavior of long transmission lines.

CAPACITANCE

Capacitance is the property of electric circuits through which electric energy is stored in an insulating medium (dielectric). Electrical capacitance exists when two conductors are separated by a dielectric, which may be air, paper, mica, porcelain, glass, or other insulating material. The effect of capacitance in a circuit is shown in Fig. 1-2.

As has previously been noted, all electric circuits contain electric resistance, inductance, and capacitance. In ac circuits, the effect of in-

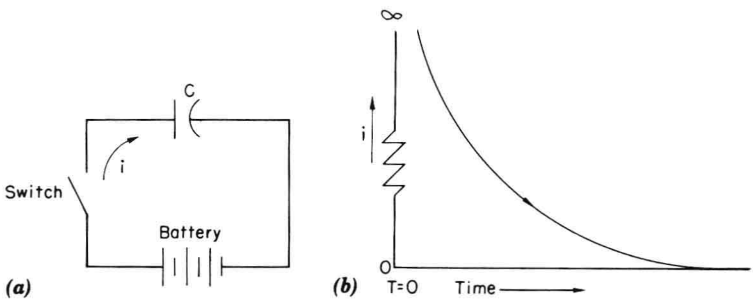

figure 1-2 When the switch is closed, current *i* immediately increases to a value limited only by the resistance in the circuit and then decreases to zero over a period of time as indicated in **(*b*)**. If the switch is opened after *i* reaches zero, no change will occur, and an electric charge (electrostatic energy) will be left on the plates of the capacitor. With a perfect dielectric (i.e., one with no loss), the charge would be retained indefinitely. In an ac circuit, since voltage is continuously changing, the effect is alternately to charge the capacitor in one polarity, discharge it, and then charge it in the opposite polarity.