C RUSSELL MASON

THE ART AND SCIENCE OF PROTECTIVE RELAYING

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THE ART AND SCIENCE OF PROTECTIVE RELAYING

TO MY WIFE, DOT WITHOUT WHOSE PATIENCE AND UNDER-
STANDING THIS BOOK WOULD NOT HAVE BEEN WRITTEN

PREFACE

"Science is systematized knowledge. Art is knowledge made efficient by skill."

Webster's Collegiate Dictionary, Fifth Edition, G. and C. Merriam Co., Springfield, Mass., 1942

This is a textbook on protective relaying. Much of the material has been used for several years as notes for teaching the subject in the Power Systems Engineering Course given by the General Electric Company. These notes were written because there was no suitable reference book available that properly presented the subject to the novice.

From the experience gained, the notes were revised to improve their clarity and to add necessary explanatory material. Therefore, the material has been tested in the classroom and it should prove useful both as a reference for teaching the subject and for the purpose of self-education.

As already intimated, the book assumes no prior knowledge of protective relaying. In fact, as the student will quickly discover, one needs to know only the fundamental principles of electrical engineering to become well acquainted with protective relaying. He will not be able to master the subject without practical experience in the field, but the subject will lose most of the mystery generally associated with it.

In spite of the elementary nature of the book, it should also be useful to the practicing relay engineer. The book contains new material, it treats many subjects in a different manner from that found elsewhere, and it may help many to understand better what they already know. At least, that has been my experience in writing the material and presenting it to the student. Also, the book contains references to basic source material that has been found to be most authoritative and useful.

Theoretical considerations that have no practical utility have been studiously avoided. Only material is included that I know is useful on the basis of over 25 years of experience. This is not to say that the book will answer every question that may arise, but it will at least help one to find the answer. Neither is the book an historical reference or a reference to foreign practices.

So far as it is possible to make it so, the book is timeless. It contains fundamental information that is applicable to present-day North American practice, but the nature of the material is such that it will be applicable whenever or wherever protective relays are involved. It follows that the book tries to be impartial to all manufacturers of protective relays. Naturally, I have had the most ready access to data, etc., pertaining to relays manufactured by the company with which I am associated, but I have conscientiously tried to avoid any taint of commercialism.

In general, proofs are avoided. References are given to source material containing proofs where such is considered necessary. There are too many worth-while things to be covered to burden the book with proofs unless they are an actual aid to a better understanding of the subject.

The references are not always to prove or confirm a point in the text, but are sometimes other opinions on the subject. With few exceptions, the references are not intended to give credit for original work or contributions, but to present the most up-to-date treatments of the subjects. In general, references are made only to publications that are easily available to the student; many other valuable contributions to the literature have been made, but they consist of conference papers and publications of individual companies or associations that are not readily available in most libraries; in this respect, it is strongly recommended that authors of such material seek eventual publication in the technical press.

This book studiously avoids photographs and nomenclature of actual relays. Such things would "date" the book, take up valuable space, and would add but little to its value. One does not need to know what a relay looks like to learn how it operates and how to apply it. A relay photograph, especially as reproducible in a book, shows practically nothing of real value. The student does not have to go far to see actual relays. Also, the manufacturers will provide well-illustrated publications.

C. Russell Mason

Schenectady, N. Y.
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1 THE PHILOSOPHY OF PROTECTIVE RELAYING

What is Protective Relaying?

We usually think of an electric power system in terms of its more impressive parts—the big generating stations, transformers, high-voltage lines, etc. While these are some of the basic elements, there are many other necessary and fascinating components. Protective relaying is one of these.

The role of protective relaying in electric-power-system design and operation is explained by a brief examination of the over-all background. There are three aspects of a power system that will serve the purposes of this examination. These aspects are as follows:

A. Normal operation.
B. Prevention of electrical failure.
C. Mitigation of the effects of electrical failure

The term "normal operation" assumes no failures of equipment, no mistakes of personnel, nor "acts of God." It involves the minimum requirements for supplying the existing load and a certain amount of anticipated future load. Some of the considerations are:

A. Choice between hydro, steam, or other sources of power.
B. Location of generating stations.
C. Transmission of power to the load.
D. Study of the load characteristics and planning for its future growth.
E. Metering.
F. Voltage and frequency regulation.
G. System operation.
H. Normal maintenance.

The provisions for normal operation involve the major expense for equipment and operation, but a system designed according to this aspect alone could not possibly meet present-day requirements. Electrical equipment failures would cause intolerable outages. There must be additional provisions to minimize damage to equipment and interruptions to the service when failures occur.

Two recourses are open: (1) to incorporate features of design aimed at preventing failures, and (2) to include provisions for mitigating the effects of failure when it occurs. Modern power-system design employs varying degrees of both recourses, as dictated by the economics of any particular situation. Notable advances continue to be made toward greater reliability. But also, increasingly greater reliance is being placed on electric power. Consequently, even though the probability of failure is decreased, the tolerance of the possible harm to the service is also decreased. But it is futile—or at least not economically justifiable—to try to prevent failures completely. Sooner or later the law of diminishing returns makes itself felt. Where this occurs will vary between systems and between parts of a system, but, when this point is reached, further expenditure for failure prevention is discouraged. It is much more profitable, then, to let some failures occur and to provide for mitigating their effects.

The type of electrical failure that causes greatest concern is the short circuit, or "fault" as it is usually called, but there are other abnormal operating conditions peculiar to certain elements of the system that also require attention. Some of the features of design and operation aimed at preventing electrical failure are:

A. Provision of adequate insulation.
B. Coordination of insulation strength with the capabilities of lightning arresters.
C. Use of overhead ground wires and low tower-footing resistance.
D. Design for mechanical strength to reduce exposure, and to minimize the likelihood of failure causable by animals, birds, insects, dirt, sleet, etc.
E. Proper operation and maintenance practices.

Some of the features of design and operation for mitigating the effects of failure are:

A. Features that mitigate the immediate effects of an electrical failure.
   1. Design to limit the magnitude of short-circuit current.[1]
      a. By avoiding too large concentrations of generating capacity.
      b. By using current-limiting impedance.
   2. Design to withstand mechanical stresses and heating owing to short-circuit currents.
   3. Time-delay undervoltage devices on circuit breakers to prevent dropping loads during momentary voltage dips.
   4. Ground-fault neutralizers (Petersen coils).
B. Features for promptly disconnecting the faulty element.
   1. Protective relaying.
   2. Circuit breakers with sufficient interrupting capacity.
   3. Fuses.

C. Features that mitigate the loss of the faulty element.
   1. Alternate circuits.
   2. Reserve generator and transformer capacity.
   3. Automatic reclosing.
D. Features that operate throughout the period from the inception of the fault until after its removal, to maintain voltage and stability.
   1. Automatic voltage regulation.
   2. Stability characteristics of generators.
E. Means for observing the effectiveness of the foregoing features.
   1. Automatic oscillographs.
   2. Efficient human observation and record keeping.
F. Frequent surveys as system changes or additions are made, to be sure that the foregoing features are still adequate.

Thus, protective relaying is one of several features of system design concerned with minimizing damage to equipment and interruptions to service when electrical failures occur. When we say that relays "protect," we mean that, together with other equipment, the relays help to minimize damage and improve service. It will be evident that all the mitigation features are dependent on one another for successfully minimizing the effects of failure. *Therefore, the capabilities and the application requirements of protective-relaying equipments should be considered concurrently with the other features.*[2] This statement is emphasized because there is sometimes a tendency to think of the protective-relaying equipment after all other design considerations are irrevocably settled. Within economic limits, an electric power system should be designed so that it can be adequately protected.

The Function of Protective Relaying

The function of protective relaying is to cause the prompt removal from service of any element of a power system when it suffers a short circuit, or when it starts to operate in any abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system. The relaying equipment is aided in this task by circuit breakers that are capable of disconnecting the faulty element when they are called upon to do so by the relaying equipment.

Circuit breakers are generally located so that each generator, transformer, bus, transmission line, etc., can be completely disconnected from the rest of the system. These circuit breakers must have sufficient capacity so that they can carry momentarily the maximum short-circuit current that can flow through them, and then interrupt this current; they must also withstand closing in on such a short circuit and then interrupting it according to certain prescribed standards.[3]

Fusing is employed where protective relays and circuit breakers are not economically justifiable.

Although the principal function of protective relaying is to mitigate the effects of short circuits, other abnormal operating conditions arise that also require the services of protective relaying. This is particularly true of generators and motors.

A secondary function of protective relaying is to provide indication of the location and type of failure. Such data not only assist in expediting repair but also, by comparison with human observation and automatic oscillograph records, they provide means for analyzing the effectiveness of the fault-prevention and mitigation features including the protective relaying itself.

Fundamental Principles of Protective Relaying

Let us consider for the moment only the relaying equipment for the protection against short circuits. There are two groups of such equipment—one which we shall call "primary" relaying, and the other "back-up" relaying. Primary relaying is the first line of defense, whereas back-up relaying functions only when primary relaying fails.

PRIMARY RELAYING

Figure 1 illustrates primary relaying. The first observation is that circuit breakers are located in the connections to each power-system element. This provision makes it possible to disconnect only a faulty element. Occasionally, a breaker between two adjacent elements may be omitted, in which event both elements must be disconnected for a failure in either one.

The second observation is that, without at this time knowing how it is accomplished, a separate zone of protection is established around each system element. The significance of this is that any failure occurring within a given zone will cause the "tripping" (i.e., opening) of all circuit breakers within that zone, and only those breakers.

It will become evident that, for failures within the region where two adjacent protective zones overlap, more breakers will be tripped than the minimum necessary to disconnect the faulty element. But, if there were no overlap, a failure in a region between zones would not lie in either zone, and therefore no breakers would be tripped. The overlap is the lesser of the two evils. The extent of the overlap is relatively small, and the probability of failure in this region is low; consequently, the tripping of too many breakers will be quite infrequent.

Finally, it will be observed that adjacent protective zones of Fig. 1 overlap *around a circuit breaker.* This is the preferred practice

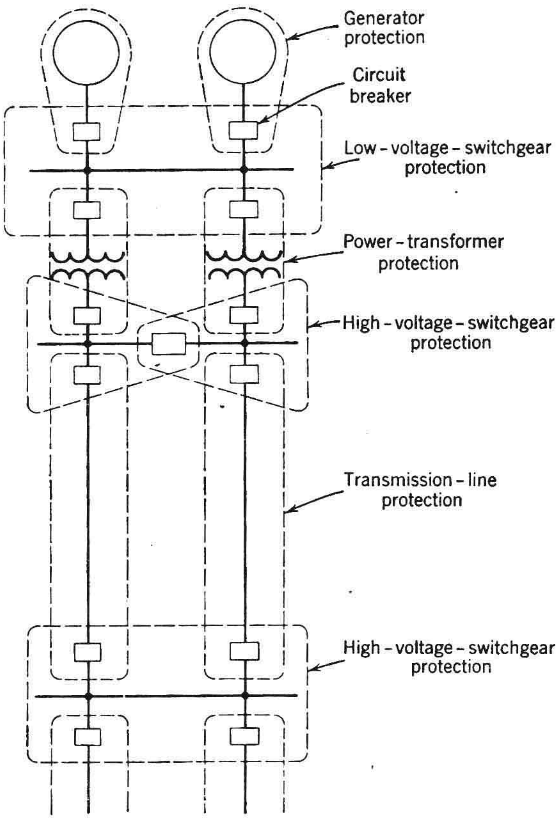

Fig. 1. One-line diagram of a portion of an electric power system illustrating primary relaying.

because, for failures anywhere except in the overlap region, the minimum number of circuit breakers need to be tripped. When it becomes desirable for economic or space-saving reasons to overlap on one side of a breaker, as is frequently true in metal-clad switchgear, the relaying equipment of the zone that overlaps the breaker must be arranged to trip not only the breakers within its zone but also one or more breakers of the adjacent zone, in order to com-