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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.
- E. 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 electiveness 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

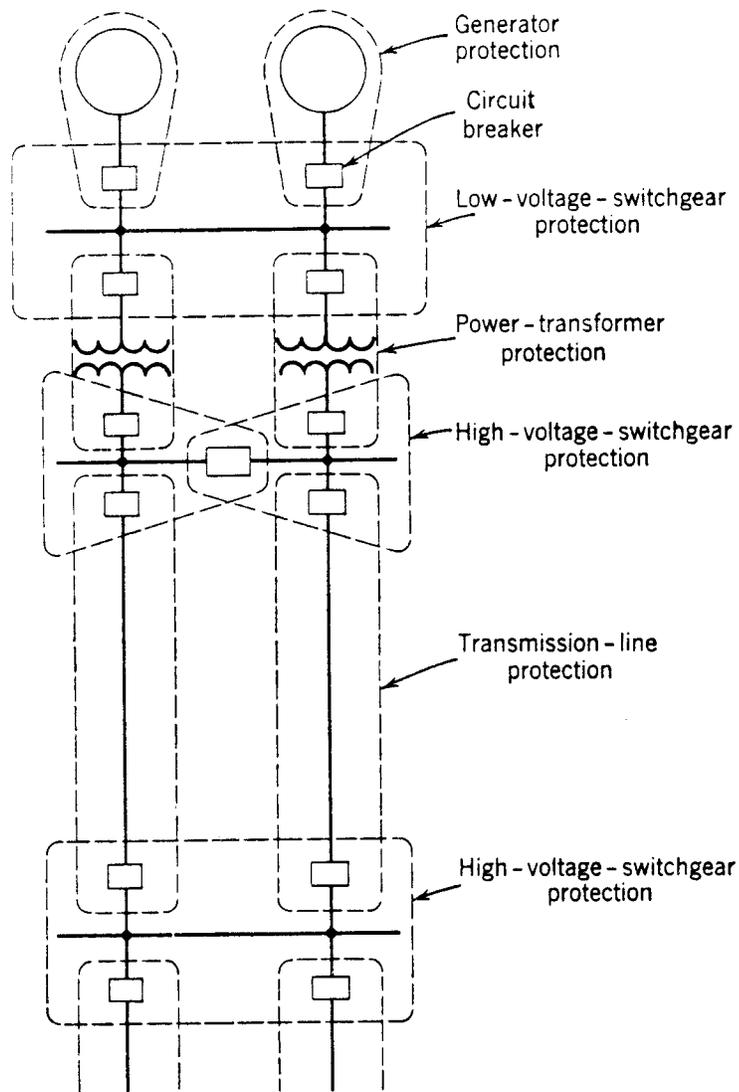


Fig. 1. One-line diagram of a portion of an electric power system illustrating primary relaying.

Figure 1 illustrates primary relaying. The first observation is that circuit breakers are located in the connections to each power 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 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 completely disconnect certain faults. This is illustrated in Fig. 2, where it can be seen that, for a short circuit at *X*, the circuit breakers of zone *B*, including breaker *C*, will be tripped; but, since the short circuit is outside zone *A*, the relaying equipment of zone *B* must also trip certain breakers in zone *A* if that is necessary to interrupt the flow of short circuit current from zone *A* to the fault. This is not a disadvantage for a fault at *X*, but the same breakers in zone *A* will be tripped unnecessarily for other faults in zone *B* to the right of breaker *C*. Whether this unnecessary tripping is objectionable will depend on the particular application.

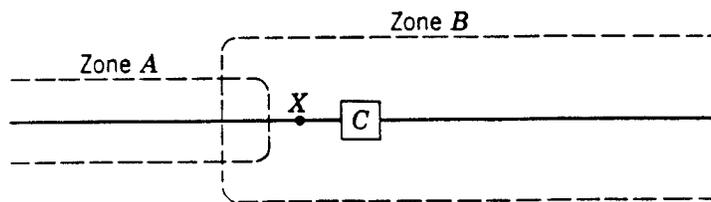


Fig. 2. Overlapping adjacent protective zones on one side of a circuit breaker.

BACK-UP RELAYING

Back-up relaying is employed only for protection against short circuits. Because short circuits are the preponderant type of power failure, there are more opportunities for failure in short primary relaying. Experience has shown that back-up relaying for other than short circuits is not economically justifiable.

A clear understanding of the possible causes of primary-relaying failure is necessary for a better appreciation of the practices involved in back-up relaying. When we say that primary relaying may fail, we mean that any of several things may happen to prevent primary relaying from causing the disconnection of a power-system fault. Primary relaying may fail because of failure in any of the following:

- A. Current or voltage supply to the relays.
- B. D-c tripping-voltage supply.
- C. Protective relays.
- D. Tripping circuit or breaker mechanism.
- E. Circuit breaker.

It is highly desirable that back-up relaying be arranged so that anything that might cause primary relaying to fail will not also cause failure of back-up relaying. It will be evident that this requirement is completely satisfied only if the back-up relays are located so that they do not employ or control anything in common with the primary relays that are to be backed up. So far as possible, the practice is to locate the back-up relays at a different station. Consider, for example, the back-up relaying for the transmission line section EF of Fig. 3. The back-up relays for this line section are normally arranged to trip breakers A , B , I , and J . Should breaker E fail to trip for a fault on the line section EF , breakers A and B are tripped; breakers A and B and their associated back-up equipment, being physically apart from the equipment that has failed, are not likely to be simultaneously affected as might be the case if breakers C and D were chosen instead.

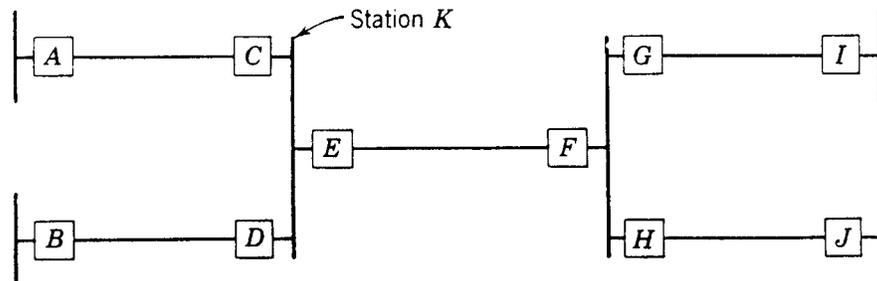


Fig. 3. Illustration for back-up protection of transmission line section EF .

The back-up relays at locations A , B , and F provide back-up protection if bus faults occur at station K . Also, the back-up relays at A and F provide back-up protection for faults in the line DB . In other words, the zone of protection of back-up relaying extends in one direction from the location of any back-up relay and at least overlaps each adjacent system element. Where adjacent line sections are of different length, the back-up relays must overreach some line sections more than others in order to provide back-up protection for the longest line.

A given set of back-up relays will provide incidental back-up protection of sorts for faults in the circuit whose breaker the back-up relays control. For example, the back-up relays that trip breaker A of Fig. 3 may also act as back-up for faults in the line section AC . However,

this duplication of protection is only an incidental benefit and is not to be relied on to the exclusion of a conventional back-up arrangement when such arrangement is possible; to differentiate between the two, this type might be called “duplicate primary relaying.”

A second function of back-up relaying is often to provide primary protection when the primary-relaying equipment is out of service for maintenance or repair.

It is perhaps evident that, when back-up relaying functions, a larger part of the system is disconnected than when primary relaying operates correctly. This is inevitable if back-up relaying is to be made independent of those factors that might cause primary relaying to fail. However, it emphasizes the importance of the second requirement of back-up relaying, that it must operate with sufficient time delay so that primary relaying will be given enough time to function if it is able to. In other words, when a short circuit occurs, both primary relaying and back-up relaying will normally start to operate, but primary relaying is expected to trip the necessary breakers to remove the short-circuited element from the system, and back-up relaying will then reset without having had time to complete its function. When a given set of relays provides back-up protection for several adjacent system elements, the slowest primary relaying of any of those adjacent elements will determine the necessary time delay of the given back-up relays.

For many applications, it is impossible to abide by the principle of complete segregation of the back-up relays. Then one tries to supply the back-up relays from sources other than those that supply the primary relays of the system element in question, and to trip other breakers. This can usually be accomplished; however, the same tripping battery may be employed in common, to save money and because it is considered only a minor risk. This subject will be treated in more detail in Chapter 14.

In extreme cases, it may even be impossible to provide any back-up protection; in such cases, greater emphasis is placed on the need for better maintenance. In fact, even with complete back-up relaying, there is still much to be gained by proper maintenance. When primary relaying fails, even though back-up relaying functions properly, the service will generally suffer more or less. Consequently, back-up relaying is not a proper substitute for good maintenance.

PROTECTION AGAINST OTHER ABNORMAL CONDITIONS

Protective relaying for other than short circuits is included in the category of primary relaying. However, since the abnormal conditions requiring protection are different for each system element, no universal overlapping arrangement of relaying is used as in short protection. Instead, each system element is independently provided with whatever relaying is required, and this relaying is arranged to trip the necessary circuit breakers which may in some cases be different from those tripped by the short-circuit relaying. As previously mentioned, back-up relaying is not employed because experience has not shown it to be economically justifiable. Frequently, however, back-up relaying for short circuits will function when other abnormal conditions occur that produce abnormal currents or voltages, and back-up protection of sorts is thereby incidentally provided.

FUNCTIONAL CHARACTERISTICS OF PROTECTIVE RELAYING

SENSITIVITY, SELECTIVITY, AND SPEED

“Sensitivity,” “selectivity” and “speed” are terms commonly used to describe the functional characteristics of any protective-relaying equipment. All of them are implied in the foregoing considerations of primary and back-up relaying. Any relaying equipment must be sufficiently *sensitive* so that it will operate reliably, when required, under the actual condition that produces the least operating tendency. It must be able to *select* between those conditions for which prompt operation is required and those for which no operation, or time-delay operation, is required. And it must operate at the required *speed*. How well any protective-relaying equipment fulfills each of these requirements must be known for each application.

The ultimate goal of protective relaying is to disconnect a faulty system element as quickly as possible. Sensitivity and selectivity are essential to assure that the proper circuit breakers will be tripped, but speed is the “pay-off.” The benefits to be gained from speed will be considered later.

RELIABILITY

That protective-relaying equipment must be reliable is a basic requirement. When protective relaying fails to function properly, the allied mitigation features are largely ineffective. Therefore, it is essential that protective-relaying equipment be inherently reliable, and that its application, installation, and maintenance be such as to assure that its maximum capabilities will be realized.

Inherent reliability is a matter of design based on long experience, and is much too extensive and detailed a subject to do justice to here. Other things being equal, simplicity and robustness contribute to reliability, but they are not of themselves the complete solution. Workmanship must be taken into account also. Contact pressure is an important measure of reliability, but the contact materials and the provisions for preventing contact contamination are fully as important. These are but a few of the many design considerations that could be mentioned.

The proper application of protective-relaying equipment involves the proper choice not only of relay equipment but also of the associated apparatus. For example, lack of suitable sources of current and voltage for energizing the relays may compromise, if not jeopardize, the protection.

Contrasted with most of the other elements of an electric power system, protective relaying stands idle most of the time. Some types of relaying equipment may have to function only once in several years. Transmission-line relays have to operate most frequently, but even they may operate only several times per year. This lack of frequent exercising of the relays and their associated equipment must be compensated for in other ways to be sure that the relaying equipment will be operable when its turn comes.

Many electric utilities provide their test and maintenance personnel with a manual that experienced people in the organization have prepared and that is kept up to date as new

types of relays are purchased. Such a manual specifies minimum test and maintenance procedure that experience has shown to be desirable. The manual is prepared in part from manufacturers' publications and in part from the utility's experience. As a consequence of standardized techniques, the results of periodic tests can be compared to detect changes or deterioration in the relays and their associated devices. Testers are encouraged to make other tests as they see fit so long as they make the tests required by the manual. If a better testing technique is devised, it is incorporated into the manual. Some organizations include information on the purpose of the relays, to give their people better appreciation of the importance of their work. Courses may be given, also. Such activity is highly recommended. Unless a person is thoroughly acquainted with relay testing and maintenance, he can do more harm than good, and he might better leave the equipment alone.

In some cases, actual field tests are made after installation and after careful preliminary testing of the individual relays. These field tests provide an excellent means for checking the over-all operation of all equipment involved.

Careful maintenance and record keeping, not only of tests during maintenance but also of relay operation during actual service, are the best assurance that the relaying equipment is in proper condition. Field testing is the best-known way of checking the equipment prior to putting it in service, but conditions may arise in actual service that were not anticipated in the tests. The best assurance that the relays are properly applied and adjusted is a record of correct operation through a sufficiently long period to include the various operating conditions that can exist. It is assuring not only when a particular relaying equipment trips the proper breakers when it should for a given fault but also when other relaying equipments properly refrain from tripping.

ARE PROTECTIVE PRACTICES BASED ON THE PROBABILITY OF FAILURE?

Protective practices are based on the probability of failure to the extent that present-day practices are the result of years of experience in which the frequency of failure undoubtedly has played a part. However, the probability of failure seldom if ever enters directly into the choice of a particular type of relaying equipment except when, for one reason or another, one finds it most difficult to apply the type that otherwise would be used. In any event, the probability of failure should be considered only together with the consequences of failure should it occur. It has been said that the justification for a given practice equals the likelihood of trouble times the cost of the trouble. Regardless of the probability of failure, no portion of a system should be entirely without protection, even if it is only back-up relaying.

PROTECTIVE RELAYING VERSUS A STATION OPERATOR

Protective relaying sometimes finds itself in competition with station operators or attendants. This is the case for protection against abnormal conditions that develop slowly enough for an operator to have time to correct the situation before any harmful consequences develop. Sometimes, an alert and skillful operator can thereby avoid having

to remove from service an important piece of equipment when its removal might be embarrassing; if protective relaying is used in such a situation, it is merely to sound an alarm. To some extent, the preference of relying on an operator has a background of some unfortunate experience with protective relaying whereby improper relay operation caused embarrassment; such an attitude is understandable, but it cannot be supported logically. Where quick and accurate action is required for the protection of important equipment, it is unwise to rely on an operator. Moreover, when trouble occurs, the operator usually has other things to do for which he is better fitted.

UNDESIRE TRIPPING VERSUS FAILURE TO TRIP WHEN DESIRED

Regardless of the rules of good relaying practice, one will occasionally have to choose which rule may be broken with the least embarrassment. When one must choose between the chance of undesired or unnecessary tripping and failure to trip when tripping is desired, the best practice is generally to choose the former. Experience has shown that, where major system shutdowns have resulted from one or the other, the failure to trip—or excessive delay in tripping—has been by far the worse offender.

THE EVALUATION OF PROTECTIVE RELAYING

Although a modern power system could not operate without protective relaying, this does not make it priceless. As in all good engineering, economics plays a large part. Although the protection engineer can usually justify expenditures for protective relaying on the basis of standard practice, circumstances may alter such concepts, and it often becomes necessary to evaluate the benefits to be gained. It is generally not a question of whether protective relaying can be justified, but of how far one should go toward investing in the best relaying available.

Like all other parts of a power system, protective relaying should be evaluated on the basis of its contribution to the best economically possible service to the customers. The contribution of protective relaying is to help the rest of the power system to function as efficiently and as effectively as possible in the face of trouble.² How protective relaying does this is as follows. By minimizing damage when failures occur, protective relaying minimizes:

- A. The cost of repairing the damage.
- B. The likelihood that the trouble may spread and involve other equipment.
- C. The time that the equipment is out of service.
- D. The loss in revenue and the strained public relations while the equipment is out of service.

By expediting the equipment's return to service, protective relaying helps to minimize the amount of equipment reserve required, since there is less likelihood of another failure before the first failure can be repaired.

The ability of protective relaying to permit fuller use of the system capacity is forcefully illustrated by system stability. Figure 4 shows how the speed of protective relaying influences the amount of power that can be transmitted without loss of synchronism when short circuits occur.⁴ More load can be carried over an existing system by speeding up the protective relaying. This has been shown to be a relatively inexpensive way to increase the transient stability limit.⁵ Where stability is a problem, protective relaying can often be evaluated against the cost of constructing additional transmission lines or switching stations.

Other circumstances will be shown later in which certain types of protective-relaying equipment can permit savings in circuit breakers and transmission lines.

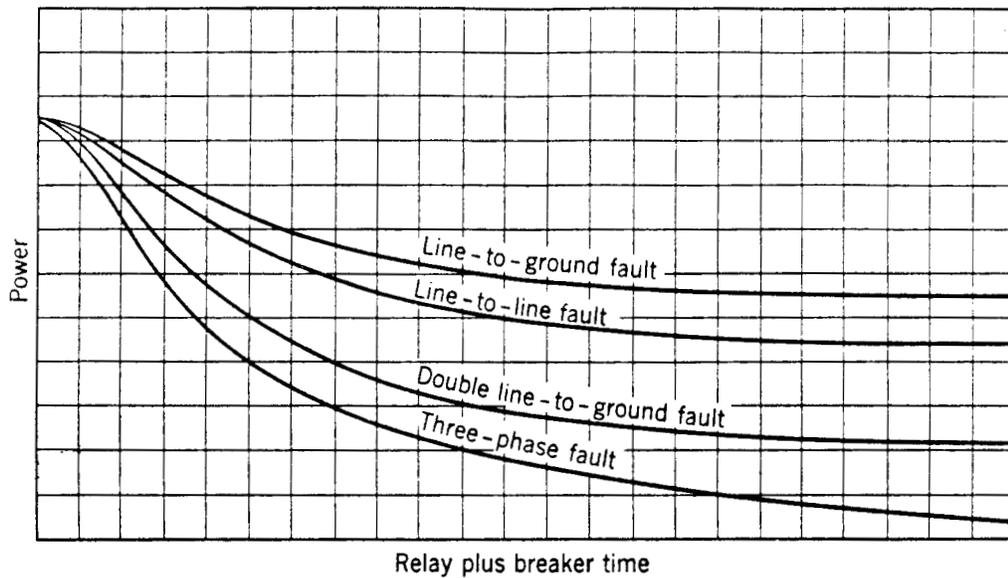


Fig. 4. Curves illustrating the relation between relay-plus-breaker time and the maximum amount of power that can be transmitted over one particular system without loss of synchronism when various faults occur.

The quality of the protective-relaying equipment can affect engineering expense in applying the relaying equipment itself. Equipment that can still operate properly when future changes are made in a system or its operation will save much future engineering and other related expense.

One should not conclude that the justifiable expense for a given protective-relaying equipment is necessarily proportional to the value or importance of the system element to be directly protected. A failure in that system element may affect the ability of the entire system to render service, and therefore that relaying equipment is actually protecting the service of the entire system. Some of the most serious shutdowns have been caused by consequential effects growing out of an original failure in relatively unimportant equipment that was not properly protected.

HOW DO PROTECTIVE RELAYS OPERATE?

Thus far, we have treated the relays themselves in a most impersonal manner, telling what they do without any regard to how they do it.

This fascinating part of the story of protective relaying will be told in much more detail later. But, in order to round out this general consideration of relaying and to prepare for what is yet to come, some explanation is in order here.

All relays used for short-circuit protection, and many other types also, operate by virtue of the current and/or voltage supplied to them by current and voltage transformers connected in various combinations to the system element that is to be protected. Through individual or relative changes in these two quantities, failures signal their presence, type, and location to the protective relays. For every type and location of failure, there is some distinctive difference in these quantities, and there are various types of protective-relaying equipments available, each of which is designed to recognize a particular difference and to operate in response to it.⁶

More possible differences exist in these quantities than one might suspect. Differences in each quantity are possible in one or more of the following:

- A. Magnitude.
- B. Frequency.
- C. Phase angle.
- D. Duration.
- E. Rate of change.
- F. Direction or order of change.
- G. Harmonics or wave shape.

Then, when both voltage and current are considered in combination, or relative to similar quantities at different locations, one can begin to realize the resources available for discriminatory purposes. It is a fortunate circumstance that, although Nature in her contrary way has imposed the burden of electric-power-system failure, she has at the same time provided us with a means for combat.

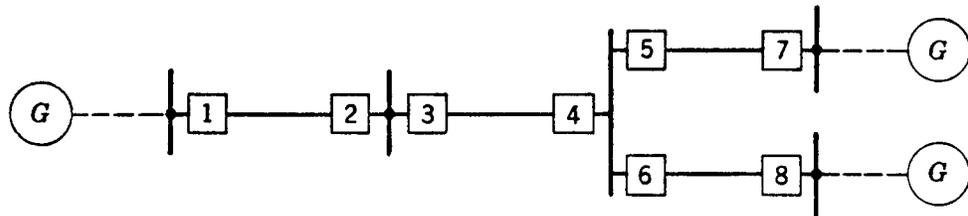


Fig. 5. Illustration for Problem 2.

PROBLEMS

1. Compare protective relaying with insurance.
2. The portion of a power system shown by the one-line diagram of Fig. 5, with generating sources back of all three ends, has conventional primary and back-up relaying. In each of the listed cases, a short circuit has occurred and certain circuit breakers have tripped as stated. Assume that the tripping of these breakers was correct under the circumstances. Where was the short circuit? Was there any failure of the protective relaying, including breakers, and if so, what failed? Assume only one failure at a time. Draw a sketch showing the overlapping of primary protective zones and the exact locations of the various faults.

Case	Breakers Tripped
<i>a</i>	4, 5, 8
<i>b</i>	3, 7, 8
<i>c</i>	3, 4, 5, 6
<i>d</i>	1, 4, 5, 6
<i>e</i>	4, 5, 7, 8
<i>f</i>	4, 5, 6

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