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Review of Principles of Protection

1.1 Introduction

The power system is an interconnected network of electrical components that are designed, installed, commissioned, and operated in accordance with international/national standards to provide a reliable supply of electricity to meet a country's electrical energy needs. Irrespective of how such components are installed, whether in the open air, underground, in-house, or even underwater, they will be subjected to vagaries of weather, undesired human action, accidents, and natural calamities. All of these, as well as the defects or abnormalities in the components themselves, can disturb the smooth operation of the power system, creating blackouts or brownouts or even causing damage to property, equipment, and human life.

Therefore, it has become mandatory to commission automatic devices that can detect such abnormal situations in the power system and prevent or clear such abnormalities discriminatively as quickly as possible to facilitate normal operation. These automatic devices are popularly known as protective relays and the selection and coordination of such relays or protective relaying have become an indispensable part of the operation of power systems.

1.2 Historical Development

Even from the very early days of the development of industrial power systems, which usually consisted of a small generator supplying a local load, the aspect of protection has been foremost in the minds of engineers.

The first protection scheme employed to protect the industrial power system was a man, the machine minder! It was his job to watch the ammeter, sniff occasionally, feel the conductors, and at the first sign of smoke, open a great knife switch on the wall, stand back, and waff out the arc with his cloth cap. However, with the continuing development of the electricity industry, the requirement for an automatic device to detect and isolate the faulty part of the power system became an urgent necessity. The first such automatic device was the fuse. These are still being used in distribution systems.

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Centralised electricity generation, interconnection of power systems, and the high level of reliability demanded by the users forced the engineers to develop this branch of engineering from the primitive level of manual monitoring to unbelievable heights within a period of little more than a century.

1.3 Faults, Fault Currents, Voltages, and Protection

Faults and abnormal conditions are a common occurrence in any part of the power system, which constitutes electrical equipment based on varying operating principles, from generators, transformers, transmission lines, circuit breakers, and many others. Such abnormalities often cause very high currents to flow, liberating a large amount of heat at the point of fault and creating voltage drops in the system.

1.3.1 Types of Faults

Types of electrical faults that can befall a power system are varied and can be categorised as short circuits, open circuits, inter-turn faults, and abnormalities due to operational errors.

Short circuits can arise in any power system component due to an abnormal connection of one or more phases to one another or earth or both. Open circuits could also occur in any power system component and the most common are joint failures and improper closing or opening of a circuit breaker or isolator legs. Inter-turn faults or short circuits between adjacent turns of the same windings of a phase are common in transformers and generators. Human or operational errors could occur when operating the power system due to erroneous operations carried out by operational staff, which may result in short circuits, open circuits, or power quality issues.

1.3.2 Currents and Voltages under Fault Situations and Protection

All electrical faults involving short circuits or open circuits can be primarily divided into two categories; namely, balanced or symmetrical faults and unbalanced or unsymmetrical faults. Symmetrical components have to be used to analyse the latter. Such currents and voltages are the only information extracted from the power system for the protection relays to perform their duty of detecting faulty parts and isolating the same discriminatively.

The most severe fault in a power system is the short circuit; this can be three-phase, phase-to-phase, or one or more phases involving the ground. In these situations, the Electro-Motive Force (EMF) is shorted by the impedances of the power system components up to the fault, and the resulting fault current will depend on

a) Type of fault: three-phase, phase-to-phase, single-phase
b) Position of the fault, as to how far down the system
c) Neutral earthing
d) Generation connected and the internal EMFs of the machines
e) Power system configuration

Fault currents and voltages under different fault conditions are given in Tables 1.1 and 1.2 respectively [1]. In the table Z_1, Z_2, and Z_3 are positive, negative, and zero sequence impedances of the network, calculated from a single equivalent source having EMF E to the faulty point.

Table 1.1 Fault currents for different faults.

	Phase sequence components			Phase current values		
Fault	$\mathbf{I_1}$	$\mathbf{I_2}$	$\mathbf{I_3}$	$\mathbf{I_a}$	$\mathbf{I_b}$	$\mathbf{I_c}$
Three-phase	$\frac{E}{Z_1}$	0	0	$\frac{E}{Z_1}$	$\frac{a^2E}{Z_1}$	$\frac{aE}{Z_1}$
Phase-to-phase	$\frac{E}{Z_1+Z_2}$	$\frac{-E}{Z_1+Z_2}$	0	0	$\frac{-j\sqrt{3}E}{Z_1+Z_2}$	$\frac{j\sqrt{3}E}{Z_1+Z_2}$
Single-phase to earth	$\frac{E}{Z_1+Z_2+Z_0}$	$\frac{E}{Z_1+Z_2+Z_0}$	$\frac{E}{Z_1+Z_2+Z_0}$	$\frac{3E}{Z_1+Z_2+Z_0}$	0	0
Two phases to earth	$\frac{(Z_2+Z_0)E}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{-Z_0E}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{-Z_2E}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$	0	$\frac{-j\sqrt{3}E(Z_0-aZ_2)}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{-j\sqrt{3}E(Z_0-a^2Z_2)}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$
Phase-to-phase + Phase-to-earth	$\frac{(4Z_2+Z_0)E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{-Z_0E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{-2Z_2E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{6Z_2E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{6Z_2E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{6Z_2E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$

where I_a, I_b, and I_c are phase currents and I_1, I_2, and I_3 are positive, negative, and zero sequence components; $a= -0.5+j0.866$.

Table 1.2 Voltages under different faults.

	Phase sequence components			Phase voltage values		
Fault	$\mathbf{V_1}$	$\mathbf{V_2}$	$\mathbf{V_3}$	$\mathbf{V_a}$	$\mathbf{V_b}$	$\mathbf{V_c}$
Three-phase	0	0	0	0	0	0
Phase-to-phase	$\frac{Z_2E}{Z_1+Z_2}$	$\frac{Z_2E}{Z_1+Z_2}$	0	$\frac{2Z_2E}{Z_1+Z_2}$	$\frac{-Z_2E}{Z_1+Z_2}$	$\frac{-Z_2E}{Z_1+Z_2}$
Single-phase to earth	$\frac{(Z_2+Z_0)E}{Z_1+Z_2+Z_0}$	$\frac{-Z_2E}{Z_1+Z_2+Z_0}$	$\frac{-Z_2E}{Z_1+Z_2+Z_0}$	0	$\frac{[(a^2-a)Z_2+(a^2-1)Z_0E}{Z_1+Z_2+Z_0}$	$\frac{[(a^2-a)Z_2+(a^2-1)Z_0E}{Z_1+Z_2+Z_0}$
Two phases to earth	$\frac{(Z_2Z_0)E}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{Z_2Z_0E}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{Z_2Z_0E}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{3(Z_2Z_0)E}{Z_1Z_2+Z_2Z_0+Z_0Z_1}$	0	0
Phase-to-phase + Phase-to-earth	$\frac{(Z_2Z_0)E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{Z_2Z_0E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{-2Z_2Z_0E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	0	$\frac{-3(Z_2Z_0)E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$	$\frac{-3(Z_2Z_0)E}{4Z_1Z_2+Z_2Z_0+Z_0Z_1}$

where V_a, V_b, and V_c are phase currents and V_1, V_2, and V_3 are positive, negative, and zero sequence components

1.4 Fault Current Contribution from Generators

A protection engineer should be aware of the fault current contributions from the different types of generators. A few decades ago, power systems were fed mainly with synchronous generators, but today the situation is vastly different, with other types of generators becoming important contributors to generation. A detailed analysis of the fault current contributions from generators that are employed in conventional plants and distributed generation plants is given in Chapter 4.

1.5 Philosophy of Protection Relaying

The primary objective of a protection relaying system is to detect faulty power system components or abnormal situations prevailing in a power system and to initiate action to isolate the appropriate system elements. This is applicable for all parts of the power system whether it is generation, transmission, or distribution. In order to fulfil this primary objective, protection philosophy shall be defined to achieve the following:

- Ensuring continuity of electricity supply.
- Facilitating normal operation by maintaining dynamic and steady state stability.
- Preventing or mitigating equipment damage.
- Minimising equipment outage times.
- Minimising system outage times.
- Minimising the extent of areas affected by outages.
- Providing data related to the faulty item/abnormal operation.

A protective relaying system alone cannot accomplish this in isolation, but it should have the ability to fulfil these in association with the other features incorporated in a power system. Basic general requirements of such a protective relaying system are as follows:

1.5.1 Selectivity

A protective relaying system has the ability to isolate only the faulty section of the circuit after the occurrence of a short circuit; this feature is known as selectivity or discrimination.

1.5.2 Speed of Operation

Fault clearing time of a protective relaying system should be kept to a minimum to minimise the damage to the equipment, maintain the power system stability, and also to maintain the normal operation of the system.

1.5.3 Sensitivity

A protective relaying system should be capable of responding to abnormalities of the power system even under minimum fault conditions and should feature a definite sensitivity, which is defined as the minutest abnormality it can respond to.

1.5.4 Reliability, Dependability, and Security

A protection relaying system should initiate tripping when required, and the ability to do so is the measure of its reliability. There are two ways in which a relaying system can be unreliable. They may fail to operate when they should operate, and they may operate when they are not expected to operate.

The dependability is the ability of the protection scheme to operate correctly when required, and security is the ability to avoid unnecessary operations. Abnormalities in certain power system components can be rare, but the relaying system must continuously be on the alert over long intervals so that it can respond to abnormalities at any moment, in accordance with the design, when occasion demands.

1.5.5 Primary and Backup Protection

Protection relays are also liable to failure and hence a “backup” is considered mandatory. Accordingly, all protection relaying systems should comprise a primary relaying system and a backup relaying system. This will ensure that all faults in the system are cleared. Backup protection can be a local backup or remote backup.

1.5.6 Unit and Non-Unit Protection

Protection systems can be either unit or non-unit. Unit protection responds to faults in the protection zone alone, and it does not respond to through faults. Non-unit systems do not have specified zone boundaries. Differential relay is a unit protection system, whereas over current relay is a non-unit system. Distance relay is a non-unit protection system, but it can be converted into unit protection using communication channels.

1.6 Review Questions

1) Why are protection systems required for power systems?
2) How do short circuits or abnormal operations affect power systems?
3) What is the first automatic protection device? Explain where these are used now.
4) What are the main functions of protective relays and those of circuit breakers?
5) Explain the general characteristics/features that define the quality of protective relaying.
6) What are primary protection, backup protection, local backup protection, and remote backup protection?
7) Define unit protection and non-unit protection.
8) Give examples for unit protection and non-unit protection schemes.

1.7 Problems

1) For the circuit shown in Figure 1.1, considering the mal-operation of relays R_2 and R_5, describe the loss of dependability and the loss of sensitivity.

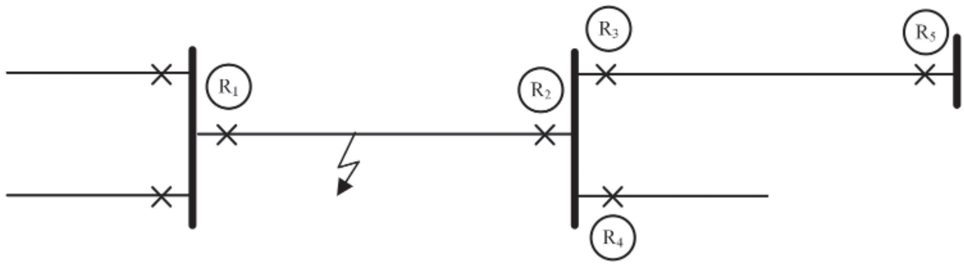

Figure 1.1 Figure for problem 1.

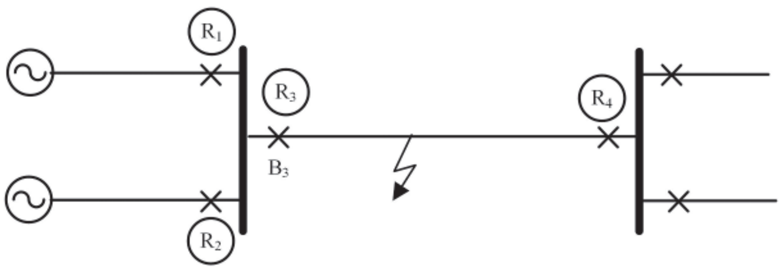

Figure 1.2 Figure for problem 2.

2) For the circuit shown in Figure 1.2, the breaker B3 did not operate for the fault shown. Which relay or relays will provide the backup protection and which relay or relays will provide primary protection?
3) The performance of an overcurrent relay was monitored over a period of one year. It was found that the relay operated 16 times and out of that 13 were correct trips. If the relay failed to issue a trip decision on 3 occasions, calculate the performance index or the percentage dependability of the protection scheme.

Reference

1 Grainger, J.J. and Stevenson, W.D. (2016). *Power System Analysis*. McGraw Hill. ISBN: 9781259008351.