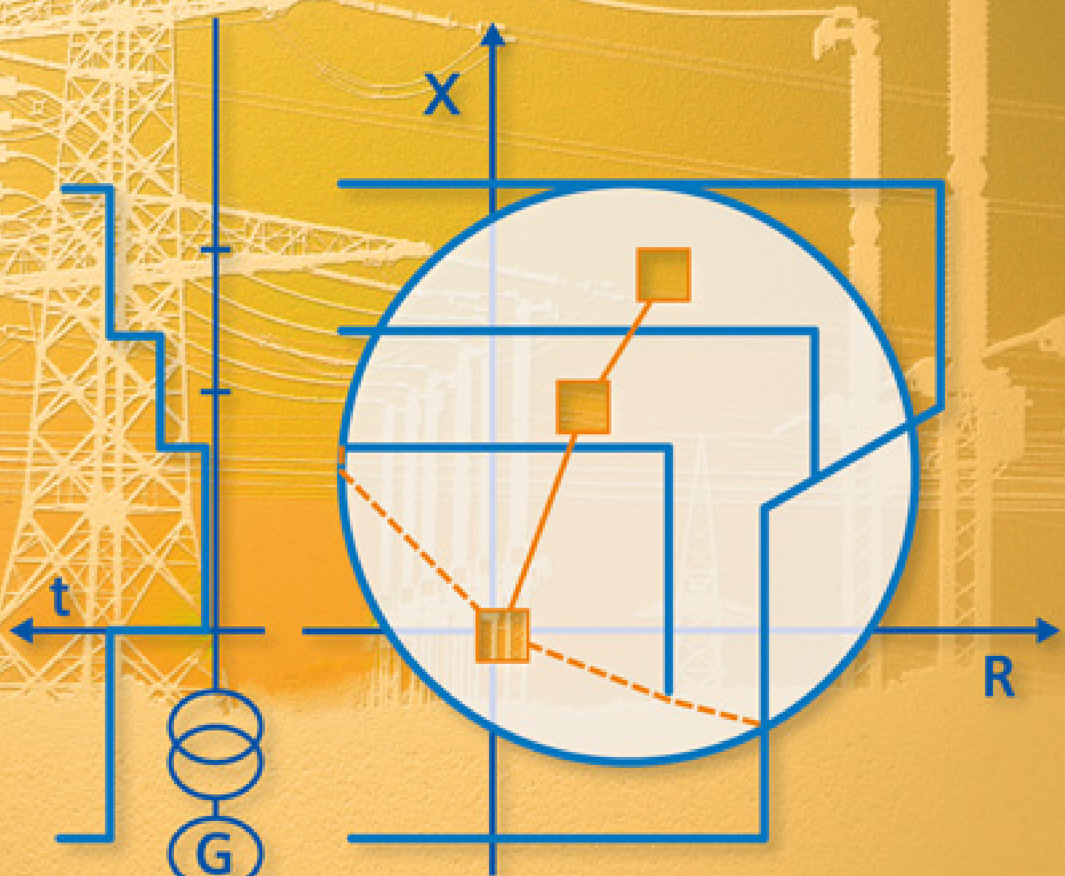
Gerhard Ziegler

Numerical Distance Protection

Principles and Applications

SIEMENS



Fourth Edition

Ziegler Numerical Distance Protection

Gerhard Ziegler (Grad. Eng.), was born in 1939, and has been working in the area of power system protection with Siemens AG in Erlangen/Nuremberg, Germany for a period of 35 years.

He was active in the areas of product support, application and project planning, marketing and sales, on a world-wide basis. He retired in 2002 but continues to work as consultant. G. Ziegler has published numerous national and international contributions in the area of power system protection. He served in international organisations for many years.

From 1993 to 2001 he was the German delegate to the IEC TC95 (measuring relays and protection equipment). He is past chairman of the Study Committee 34 (protection and local control) and Honorary Member of CIGRE.

Numerical Distance Protection

Principles and Applications

by Gerhard Ziegler

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Preface
to the First Edition

Distance protection provides short-circuit protection for universal application. It provides the basis for network protection in transmission systems and meshed distribution systems. While classic distance protection, based on electro-mechanical or static technology, are still in wide use, the state of the art today are multi-functional micro-processor devices. They communicate with centralised control systems and may be operated with personal computers locally or from remote. The basic operating principles of distance protection also apply to the new technology. Numerical signal processing, and intelligent evaluation algorithms facilitate measuring techniques with increased accuracy and protection functions with improved selectivity. The large degree of functional integration along with continuous self-monitoring results in the space-saving protection concepts, as well as economical maintenance strategies.

The book at hand initially covers the general principles of distance protection, thereby addressing the particular influence of numerical technology. The emphasis is placed on the practical application of numerical distance relays in power systems. The behaviour of the distance protection during varying fault and system conditions is extensively analysed. Procedures and equations for practical application are derived.

As the device design is manufacturer-specific, and subject to relatively rapid change, particular device configurations are only addressed in-so-far as this is necessary for general understanding. The Siemens device range 7SA is used as an illustrative example. The general statements however also apply to other manufacturers. Furthermore, reference is made to the documentation provided by the manufacturers.

Finally, the current practice in relation to distance protection application in utility and industrial systems is described. The choice of topics and examples is based on the authors extensive experience in the area of power system protection. The queries and problems experienced by users have therefore directly or indirectly contributed to this book.

This books is aimed at students and young engineers who wish to familiarise themselves with the subject of distance protection and its application as well as the experienced user, entering the area of numerical distance protection. Furthermore it serves as a reference guide for solving particular application problems.

Nuremberg, July 1999 Gerhard Ziegler

Preface

to the fourth edition

The fourth edition of this book appears nearly 12 years after the first edition and about 3 years after the third edition.

Numerical relays have in the meantime developed into smart IEDs (Intelligent Electronic Devices) with many integrated functions. Local and remote communication via dedicated optic fibers and data networks is common state of the art. In total, the protection performance has improved considerably.

Digital protection technology has reached a widely mature state. The emphasis of development has since some years shifted more to communication and substation automation.

The function principles of numerical relays and their application in practice are well established and have not significantly changed in the recent years.

The contents of the third edition of this book could therefore be left without major changes. New sections about distance protection of cables and auto-transformers have been added.

The author hopes that the book will further be world-wide accepted with such great interest by beginners and experts in the field of protective relaying.

Nuremberg, December 2010 Gerhard Ziegler

Contents

1 Introduction

Distance protection is a universal short- circuit protection.

It's mode of operation is based on the measurement and evaluation of the short- circuit impedance, which in the classic case is proportional to the distance to the fault.

Area of application

Distance protection forms the basis for network protection in transmission, as well as interconnected distribution networks.

Thereby it acts as the main protection for overhead lines and cables and in addition functions as backup protection for adjoining parts of the network, such as busbars, transformers and further feeders.

Distance protection is faster and more selective than overcurrent protection. It is also less susceptible to changes in the relative source impedances and system conditions.

A further advantage of numerical distance protection is the integrated fault location function.

Therefore it is also applied in radial networks.

Its tripping time is approximately one to two cycles (20 to 40 ms at 50 Hz) in the first zone for faults within the first 80 to 90% of the line length. In the second zone, for faults on the last 10 to 20% of the protected feeder, the tripping time is approximately 300 to 400 ms. Further zones acting as remote backup protection accordingly follow with longer set grading times.

With a communication channel between the two line-ends (pilot wire, power line carrier, radio link or optical fibre) the distance protection can be upgraded to a comparison protection scheme with absolute selectivity. It then facilitates fast tripping of short circuits on 100% of the line length similar to a differential protection scheme, whilst in addition providing remote backup protection for adjoining parts of the network.

The distance protection communication only requires a narrow band width channel, as no measured values, but only "GO/NO GO" signals are transmitted. These distance protection schemes with signal transmission appear in various forms, particularly in HV and EHV networks.

Finally the distance protection is also applied as backup protection for large generator and transformer blocks, where high pick-up sensitivity along with short tripping times are required.

Technical advances

In 1920 distance protection was introduced and it has since then undergone continuous development – from induction disk measuring elements to moving coil technology, and further to analogue static relays with operational amplifiers. Hereby the accuracy and selectivity were approved upon substantially. The tripping time was also improved by a factor ten, from the original several hundred to the present few tens of milliseconds. A quantum leap in the development of distance protection was achieved roundabout 1985, when microprocessor technology was introduced [1.1-1.4].

The numerical devices are intelligent. They can store information and communicate with peripherals. These capabilities introduce fundamentally new concepts for the improvement of protection quality. For the application and management of protection fundamentally new aspects result. At the same time the further developments of distance protection correspond to the higher demands on protection systems, resulting from the growing complexity of the transmission and distribution networks and the increased utilisation of the plant. [1.9]

Numerical distance protection

The discreet signal processing and the numerical mode of measurement allows a higher accuracy and shorter tripping times with exact filter algorithms and the application of adaptive processes. Intelligent evaluation routines furthermore allow improved selectivity, even during complex fault situations. Over and above this the cost/performance ratio was dramatically improved [1.5-1.8].

The modern devices are multifunctional and thereby can implement the protection functions as well as additional functions for other tasks such as e.g. operational measurements and disturbance recordings. Only one device for main and one device for backup protection (when applied) is therefore required at each line end. By means of the integrated self monitoring the transition from the expensive preventive maintenance to the more cost effective condition based maintenance and testing is achieved.

The numerical devices also allow for the operation with PC or the integration into network control systems, via serial interfaces. Thereby several new aspects arise for the configuration, installation, commissioning and maintenance.

2 Definitions

In this document the following terminology is used.

Where the definitions correspond to IEC60050-448: “International Electro-technical Vocabulary – Chapter 448: Power System Protection”, the relevant reference number is indicated [2.1]:

Distance protection

A non-unit protection whose operation and selectivity depend on local measurement of electrical quantities from which the equivalent to the fault is evaluated by comparing with zone settings [448-14-01].

Static relay (protection)

Analogue electronic relay generation using transistors, operational amplifiers and logic gates. In the US called solid-sate relay (protection).

Numerical distance protection (relay)

Fully digital distance protection utilising microprocessor technology with analogue to digital conversion of the measured values (current and voltage), computed (numerical) distance determination and digital processing logic. Sometimes the designation computer relay has also been used. The term “digital distance relay” was originally used to designate a previous generation relay with analogue measurement circuits and digital coincidence time measurement (angle measurement), using microprocessors. In the US, the term “digital distance protection” has always been used in the meaning of numerical protection. Nowadays, both terms are used in parallel.

Digital distance protection

See “numerical distance protection”.

Distance zones

The reaches of the measuring elements of distance protection, in a power system [448-14-02].

Under- and/or overreach

Mode of operation of the distance protection where the fastest zone is set with a reach which is shorter (underreach), or longer (overreach) than the protected zone [448-14-05/07].

Zone limit (cut-off distance, balance point, set point)

Measured impedance corresponding to the zone end.

Transient overreach

Operation of a distance zone for a larger value of impedance than that for which it is adjusted to operate under steady state condition [15]. This tendency occurs with offset of the short circuit current initially after fault inception. Conventional relays used a "line replica" shunt in the current path to minimise this effect. Numerical relays avoid the overreach by digital filtering of the DC component and adaptive control of the zone reach.

Impedance characteristic (relay)

Distance zone characteristic with constant impedance reach (Circle in the impedance plane centred at the origin of the R-X diagram). When used as directional zone, a directional characteristic (e.g. straight line) must be added. When the circle is shifted in the R-X diagram, we get a modified or offset impedance-type characteristic.

Impedance relay

Originally this term designated a relay with impedance circle characteristic. Impedance however is a generic term including resistance and reactance alone or a combination of the two. In this sense, the term impedance relay is often used as generic term equivalent to distance relay.

MHO (Admittance) characteristic (relay)

Circle characteristic which passes through the origin of the R-X-diagram. It is therefore inherently directional. The name is due to the fact that the MHO circle corresponds to a straight line in the admittance (1/OHM) plain.

Polarisation

Providing a relay with directional sensitivity.

Cross polarisation

Polarisation of a relay for directionality using some portion of the healthy (unfaulted) phase voltage(s). In many cases *quadrature polarisation* is used. In this case the polarising voltage is in quadrature to the faulted phase voltage. Also the positive-sequence voltage is sometimes used for polarisation.

Polarised MHO characteristic

The traditional MHO relay with a circle passing through the origin of the R-X diagram uses the voltage of the short-circuit loop (faulted phase(s) voltage) as polarising quantity. It is more precisely called self polarised MHO relay.

The *cross polarised MHO* version adds a certain percentage of healthy phase(s) voltage to the polarising voltage to ensure unlimited direction sensitivity for close-up zero-voltage faults. In consequence, the circle extends in negative X-direction for forward faults depending on the source impedance and draws together excluding the origin in case of reverse faults (see paragraph 3.4.2).

Reactance characteristic (relay)

Straight line characteristic parallel to the R-axis with constant X-reach. The reach in R-direction is unlimited. The reactance characteristic must therefore be combined with a starter characteristic (e.g. MHO type)

Quadrilateral characteristic (relay)

As the name implies, the characteristic is composed of four straight lines.

Angle-impedance (OHM) characteristic

This term designates a straight line characteristic in the R-X plane which is inclined by an angle (often the line angle) against the R-axis. A pair of these straight lines is called blinder characteristic ("blinders") and is used to limit the zone reach, e.g. of a MHO relay, in positive and negative R-direction against load encroachment (see paragraph 3.1.6).

Load blocking zone (load cut out)

A wedge shaped area which is cut out of distance zones to reduce the reach in R-direction and to allow higher loading of the relay (line) (see 6.2.3 and 6.3.2).

Loadability of distance relays

As the line load increases, the measured load impedance becomes lower and encroaches the distance zones. The load MVA at which the farthest reaching zone (starting or 3rd zone) is on the verge of operation, is called the loadability limit of the relay (see 6.2.3).

Measuring system (measuring element)

Module for the measurement of the fault distance and direction, including starting characteristics. The inputs are the short- circuit current and voltage. An active signal appears at the output when the fault lies within the corresponding zone, i.e. when the measuring system picks up.

Conventional relays used an electro-mechanical or static measuring system. With numerical relays the measuring system is a software module for the calculation of the loop impedance and for the value comparison with the set zone characteristic.

Full scheme distance protection (non-switched)

Distance protection generally having separate measuring elements for each type of phase-to-phase fault and for each type of phase-to-earth fault and for each zone measurement [448-14-03].

For numerical protection this implies that all ph-ph and all ph-E loop impedances are simultaneously computed and compared with the zone limits (e.g. 7SA6 or 7SA522).

Switched distance protection

Distance protection generally having only one measurement element for all power system faults and/or for all zones [448-14-04].

In case of numerical protection the term “switched” is not applicable as all measured values are continuously sampled and stored in a buffer. There is no HW-switching in the measuring circuits. Relays which use a fault detector controlled loop selection and only evaluate one fault loop for the distance measurement may be called “single system” distance relays (earlier digital relay versions, e.g. 7SA511).

Switched distance protection (multiple measuring system)

Distance protection with multiple measuring systems need only simplified loop selection. Three measuring systems are normally connected in delta for phase faults and are switched to wye connection in case of single phase to earth faults. (This variant was common in Germany in electromechanical EHV protection, e.g. type R3Z27.)

Protection using telecommunication

Protection requiring telecommunication between the ends of the protected section in a power system [448-15-01]. In US called *pilot protection*.

Distance protection with teleprotection channel

Distance protection requiring telecommunication between the ends of the protected section in a power system [according to 448-15-01].

Distance protection in permissive mode

A distance protection, in which the receipt of a signal permits the local protection to initiate tripping.

Distance protection blocking mode

A distance protection, in which the receipt of a signal blocks the local protection from initiating tripping [448-14-10]

Starting time

The time required from fault incidence until the starting (pick-up) of the measuring system (e.g. $I > I_{\text{pick-up}}$, or $Z < Z_{\text{starting}}$). Normally when this time is expired, a further function is released or blocked and an alarm is initiated. A trip command is only generated after evaluation of the tripping logic or following the expiry of a set delay time.

Reset ratio

This is the ratio of the pick-up to drop-off level of a measuring system. This difference is required to prevent intermittent pick-up and drop-off (chattering) of the measuring system. The reset ratio is smaller than 1 for measuring systems that pick up on increasing measured values (e.g. 0.95 for the overcurrent starting) and greater than 1 for measuring systems that pick up on decaying measured values (e.g. 1.05 for the impedance starting).

Reset time

The time during which the output signal is picked up after the measured signal has dropped below the re-set level of the measuring system.[1] The reset time of the starting, after interruption of the short-circuit current, is the most pertinent in the case of distance protection. This time is required to calculate the grading times (refer to paragraph 3.1.14).

Tripping time

The tripping time of the distance protection is the time measured from fault inception until the closing of the trip contacts. The tripping time of the undelayed fast tripping stage or typical tripping time is stated in the technical data sheet. However, this tripping time is not constant. Several factors influence it (short-circuit voltage and current as well as fault location). This dependence is usually shown as a diagram (profile curves). To determine the tripping time of the protection system (scheme), possible delays of signal transmission and channels and external trip relays must be added.

Grading times

Set delay times of the back-up zones.

End zone time

In Germany the starting element of the distance protection is utilised as remote back-up. Following a long time delay the starting element issues a trip. For this function there is a directional end zone time and a non-directional end zone time.

[1] For impedance zones the reverse applies: during starting the measured impedance drops below Z_A. To reset, the measured impedance must exceed the reset level ($Z_R = 1.05\ Z_A$).

Contour diagram

Family of isochronic time curves plotted in a diagram of fault location (% of zone reach) versus SIR (the ratio of source to line (zone reach) impedance).

Automatic reclosure (ARC)

On overhead lines most faults are of a transient nature and disappear when the infeed is switched off. After fault clearance the line can be returned to service. This is usually implemented with an ARC after a short time delay (dead time). In some cases a further reclose attempt is made if the first one is not successful – multiple shot ARC.

Short-circuit loop (fault loop)

The short-circuit current path through the system from the infeed to the fault location and back. In the case of distance protection this refers to the short circuit current path from the relay location to the fault location and back.

Short-circuit voltage (faulted loop voltage)

This terms refers to the voltage on the short-circuited loop (fault loop). In the case of distance protection this refers to the voltage between the faulted phases (phase to phase short-circuit) or between a faulted phase and earth (phase to earth short-circuit), at the relay location. The short-circuit voltage is required for the distance measurement. When this voltage is used for determining the direction, it is referred to as the faulted loop voltage.

Unfaulted loop voltage (healthy phase voltage)

To determine the fault direction (fault location in front of or behind relay location), the modern distance protection utilises measured voltages that are not affected by the fault, e.g. the voltage $U_{\mathrm{L2\text{-}L3}}$ for a short-circuit L1-E. An infinite directional measurement sensitivity is achieved in this manner. This is the case even for close-in faults, where the faulted loop voltage is too small for a reliable measurement (refer to paragraph 3.3.2).

Short-circuit impedance

Impedance in the short-circuit between the faulted phase and earth or between the faulted phases. In terms of the distance measurement, the short-circuit impedance refers to the impedance between the point of connection of the relay measured voltage and the fault location. In connection with short-circuit current calculations this term refers to the impedance of the total short circuit loop from the infeed to the fault location.

Apparent impedance

The impedance to a fault as seen by the a distance relay is determined by the current and voltage applied to the relay. It may be different from the actual impedance because of current infeed or outfeed at some point between the relay and the fault, or due to remote infeed in case of resistance faults (see 3.5.1 and 3.5.2). In the healthy phase measuring elements impedances appear that depend on fault- and pre-fault load conditions. They approach distance zones and may cause overfunction endangering phase selective tripping. This can be avoided by restricted zone setting or special phase selectors (see 3.1.6). During load the distance relay measures an apparent impedance according to the actual voltage and current at the relay location. During overload and power swing these impedances approach the distance zones and may cause false tripping. This must be prevented by restricted setting of the zone reach in R-direction and the use of power swing blocking features (see 3.1.11).

Source impedance

For a particular fault location, the source impedance is that part of the impedance in the short-circuit loop, which lies between the source voltage (voltage delivering the short-circuit current) and the point of connection of the relay measured voltage.

Impedance ratio (SIR)

At a particular point of measurement this refers to the ratio of the source impedance to the short circuit impedance (impedance of the protected zone) [448-14-14].

This is referred to as the system or source impedance ratio (SIR). It is a measure for the magnitude of the faulted loop voltage seen by the relay.

Load impedance

At a particular point of measurement this refers to the quotient of the phase to neutral voltage (line voltage) over the phase-current while load current is flowing [448-14-15].

Fault resistance

This refers to the resistance between the phase-conductors or between the phase-conductor and earth at the fault location.

Phasor

In this book the phasor notation is used for electrical signals:

$$\underline{A} = A \cdot e^{j\varphi} = A \cdot [\cos\varphi + j\sin\varphi] = B + jC$$

Whereby A refers to the rms (root mean square) value of the current, voltage or power, and φ to their phase angle at the time $t = 0$.

This representation is also extended to include impedances which actually are not time dependant.

3 Mode of Operation

This chapter will provide a general introduction to distance protection. Based on this, the following chapters will, in detail, deal with the mode of operation and applications of numerical distance protection.

3.1 Fundamentals of distance protection

3.1.1 Concept

Distance protection determines the fault impedance from the measured short-circuit voltage and current at the relay location (figure 3.1).

The measured fault impedance is then compared with the known line impedance. If the measured fault impedance is smaller than the set line impedance, an internal fault is detected and a trip command issued to the circuit-breaker.

This implies that the distance protection in its simplest form can reach a protection decision with the measured voltage and current at the relay location. For this basic protection decision no further information is required and the protection therefore does not have to depend on any additional equipment or signal transmission channels.

Due to inaccuracies in the distance measurement, resulting from measuring errors, CT errors and the inaccuracy of the line impedance, which is usually based on a calculation and not a measurement, a protection reach setting of 100% of the line length with a dis-

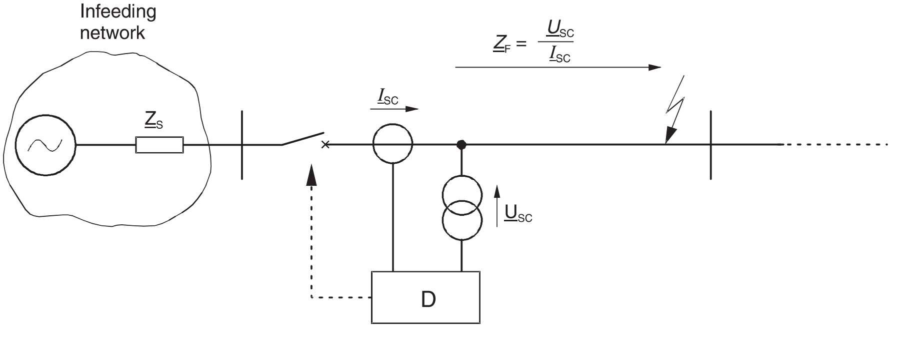


Figure 3.1 Distance protection principle, measurement of fault impedance

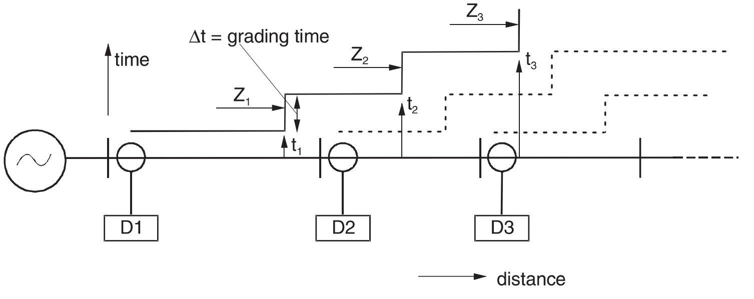


Figure 3.2 Distance protection principle, graded distance zones

tance zone is not possible in practice. A security margin (10-15%) from the remote end of the line must be selected for the so called under-reaching stage (1st zone) to ensure secure protection selection between internal and external faults (figure 3.2).

The remainder of the line is covered by an over-reaching stage (2nd zone), which, to ensure selectivity, must be time-delayed (graded) relative to the protection of the adjacent line. In the case of electro-mechanical protection this grading time is 400-500 ms and 250-300 ms in the case of analogue static and numerical protection. Considered in this grading time are the operating time (switching time) of the downstream circuit-breaker, the over-shoot of the distance measuring elements and a security margin (refer to paragraph 3.1.14: grading plan).

Contrary to differential protection, which exhibits absolute selectivity (its protected zone is exactly defined by the location of the current-transformers at both line ends), the distance protection (in its simplest form without a teleprotection supplement) does not exhibit absolute selectivity. Selective tripping must be ensured by time grading with adjacent protection.

However, distance protection additionally provides the option of back-up protection for the adjacent lines. The second stage (over-reaching zone) is used for this purpose. It reaches through the adjacent busbar and into the neighbouring lines. A further third stage is usually applied to protect the entire length of the neighbouring lines, if practicable (figure 3.2).

The co-ordination of the zone reach and time settings is achieved with a so-called grading plan (refer to paragraph 3.1.14).

3.1.2 Relay impedance (secondary impedance)

Distance protection relays are implemented as so-called secondary relays, i.e. they are fed with current and voltage measured signals from the primary system (overhead line) via instrument transformers (CT and VT). The relay therefore measures a secondary impedance which results from the transformation ratios of the CT and VT:

$$Z_{\text{sec}} = \frac{I_{\text{prim}}/I_{\text{sec}}}{U_{\text{prim}}/U_{\text{sec}}} \cdot Z_{\text{prim}} \tag{3-1}$$

Example:

Rated system voltage: $U_{\text{prim}} = 110$ kV
CT ratio: $I_{\text{prim}} / I_{\text{sec}} = 600 / 1$ A
VT ratio: $U_{\text{prim}} / U_{\text{sec}} = 110$ kV $/ 100$ Volt

$$Z_{\text{sec}} = \frac{600/1}{110/0.1} = 0.545 \cdot Z_{\text{prim}}$$

The grading plans are normally done with primary impedances.

The relay settings are done with secondary impedances as the testing of the relay is done with secondary signals. Therefore the relay impedance values must always be converted using equation (3-1).

3.1.3 Impedance diagram

To the protection engineer the impedance diagram is an essential tool for the evaluation of the behaviour of distance protection. In this diagram the relay characteristic and the measured load and short-circuit impedance are represented in the complex R-X plane (figure 3.3). In this diagram, the relation of these three impedance components are a clear indicator of the relay performance in the system.

During normal system operation the measured impedance corresponds to the load impedance. Its magnitude is inversely proportional to the amount of transferred load ($Z_{\text{load}} = U_{\text{line}}^2 / P_{\text{load}}$). The angle between current and voltage during this condition corresponds to the load angle φ_{L} (figure 3.3). It is dependent on the ratio between the real and reactive power ($\varphi_{\text{load}} = \operatorname{atan}[P_{\text{reactive}} / \text{P}_{\text{real}}]$).

After fault inception the measured impedance jumps to the short-circuit impedance, which is usually smaller than the load impedance. Its value corresponds to the line impedance between the relay location and the fault location (close-in fault Z_{LF1} or remote fault Z_{LF2}). When arc resistance or fault resistance at the fault location is present, an additional resistive component (R_{F}) is added to the line impedance. The angle that is now measured between short-circuit current and short-circuit voltage is the short circuit angle φ_{SC}.

The operating characteristic of distance protection is defined by a fixed shape in the impedance diagram.[1]

Herewith the fault area is isolated from the load area, and the reach of the distance zones is determined. Over and above this it becomes apparent whether the set reach in R-direction (also referred to as arc resistance tolerance) is adequate for the expected fault resistance. Finally a directional characteristic defines two impedance areas, by means of which the relay establishes whether a short-circuit is in the forward or reverse direction.

[1] When healthy phase voltages are used, the shape of the zone characteristic is changed in accordance with the source impedance. This is elaborately elucidated in paragraph 3.3.2.

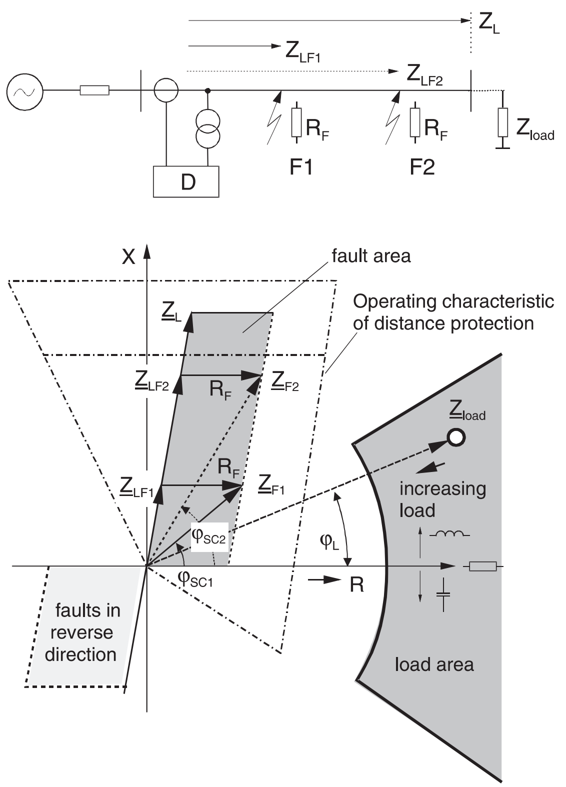


Figure 3.3
Load and short-circuit impedance

The traditional relay impedance characteristics were geometric figures made up of straight lines and circles or sectors of circles. This restriction was due to the limitations of analogue measuring techniques.

The increase in processing power of numerical protection relays liberated the choice of operating characteristics and allowed for their optimisation. This will be discussed further below.

3.1.4 Distance measurement

Conventional relays compared the short circuit impedance with the line replica impedance to determine if the fault is in- or outside the protected zone. Electro-mechanical relays manufactured in Germany used a rectifier bridge circuit as an impedance balance. Figure 3.4a shows the principle of this measuring system. The shown equation corresponds to a circle in the impedance plane (figure 3.4b). With appropriate modification of the measuring circuit the circle can be moved in the impedance plane (figure 3.5). A better fault resistance coverage (arc compensation) is achieved in this manner [3.1].

The English and American manufacturers utilised a measuring technique based on the Ferraris principle, with induction relays (figure 3.6a). In this case the moving cup (mobile drum) is equivalent to the rotor of the induction motor. The cup carries the

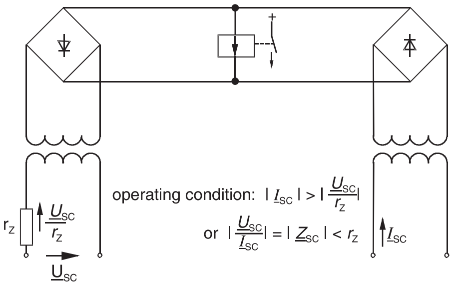


Figure 3.4a Rectified bridge comparator

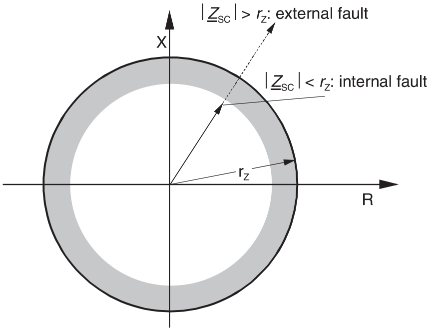


Figure 3.4b Impedance circle

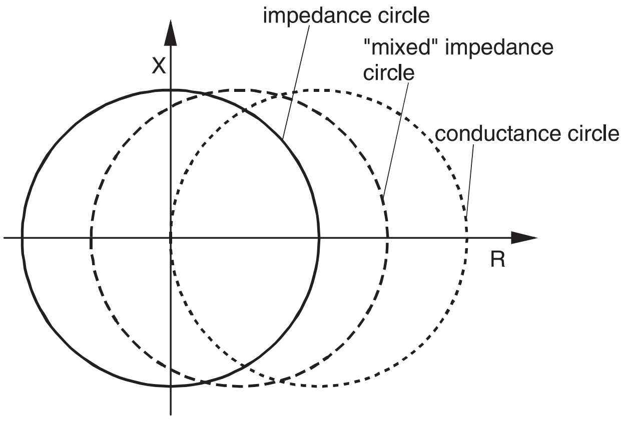


Figure 3.5
Tripping characteristic of the electro-mechanical protection (German manufacturers)

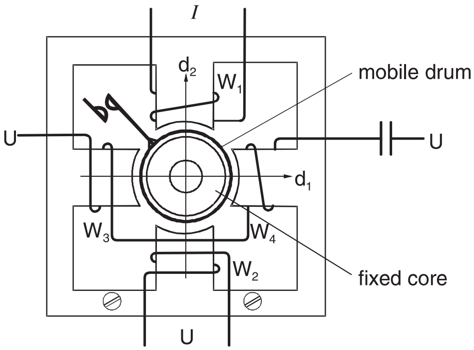
rotor currents while the magnetic circuit is completed through the stationary magnetic yokes and a fixed core. With variations of the measuring circuit, the circular and other characteristics (straight lines, lenses) can also be generated in the impedance plane.

The best known characteristic is the MHO-circle (admittance circle) (figure 3.6b) [3.2]. The circumference of this circle passes through the origin of X-R diagram and therefore inherently combines directional and distance measurement (self-polarised MHO circle). This provided an economical advantage at the times of electro-mechanical and analogue static relaying technologies. But, still today, with digital technology, this type of characteristic is preferred in the US, with the exception of ground fault distance protection of short lines where quadrilateral characteristics have been introduced to extend fault resistance coverage (see further below).

The set relay impedance Z_R defines the reach of the zone. The angle Θ is known as the Relay Characteristic Angle (RCA).

The impedance reach, dependent on the short circuit angle, is given by the formula:

$$Z = Z_R \cdot [\cos(\theta - \varphi)] \qquad (3\text{-}2)$$



$$U_{SC} \cdot I_{SC} \cdot \cos(\varphi - \Theta) \leq \frac{1}{Z_R} U_{SC}^2$$

$$\frac{U_{SC}}{I_{SC}} = Z_{SC} < Z_R \cdot \cos(\varphi - \Theta)$$

W_1: operate
W_2: restrain
W_3+W_4: polarise

Figure 3.6a Induction cup relay

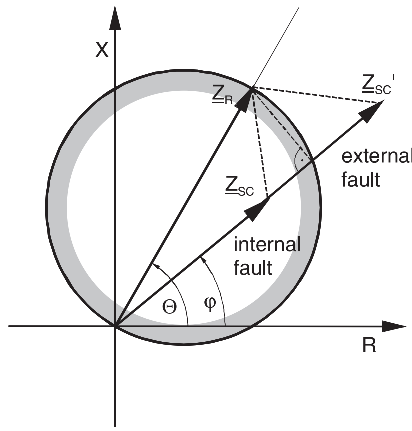


Figure 3.6b MHO characteristic

The setting of θ is normally adapted to the impedance angle of the protected line so that Z_R corresponds to a replica of the line. This was important with high speed electro-mechanical and static relays, because they used a transactor (line replica impedance) to eliminate the impact of the DC component of the fault current on the distance measurement (tendency to overreach). In case of short lines, it was general practice to set the RCA lower than the line impedance angle to improve the arc compensation. The transient error caused by the not ideal compensation of the current offset was in general tolerable, in particular with slower relays. In the extreme case, with $\theta = 0°$, we arrive at the so-called conductance circle, shown in figure 3.5. This relay characteristic was used in Germany with the electro-mechanical relays for the distribution network, in particular on cables where the short circuit angle is below 30 degrees. For the distance protection measurement only the reactance component X_F of the fault impedance can be used to effectively determine the distance to fault. The resistive component may vary due to the indeterminate arc resistance (fault resistance) at the fault location. The reach limit in X-direction should therefore be as flat as possible, running parallel to the R-axis (ideally a straight reactance line). The reach in R-direction must be limited to prevent encroachment of load impedances. Electro-mechanical relays attempted to achieve this with a combination of circles and straight lines (figure 3.7).

There is a MHO-circle with healthy phase voltage polarisation[1] (called polarised MHO or cross polarised MHO) which provides an improved arc resistance reserve (figure 3.8). In this case the diameter of the circle changes to include the source impedance (for faults in forward (line) direction). A satisfactory resistance coverage is however only achieved with relatively weak in-feeds, i.e. large source impedances [3.3].

[1] The implementation of healthy phase voltages by the distance protection is referred to in paragraph 3.3.2.

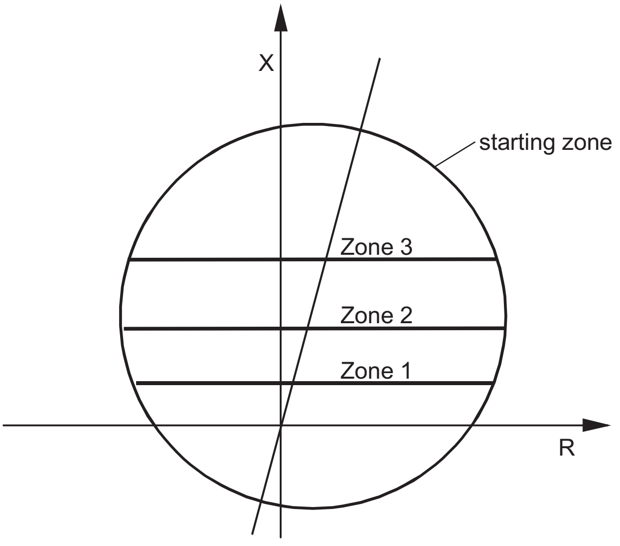


Figure 3.7
Combined circle- and straight line characteristic

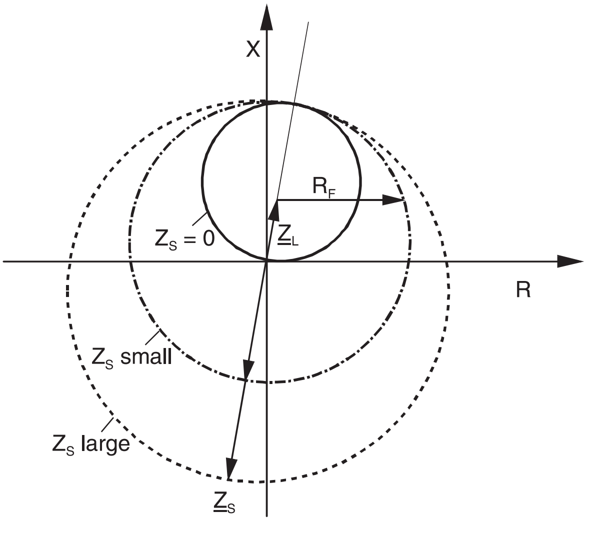


Figure 3.8
Cross polarised MHO circle (for faults in forward (line) direction)

In this regard the quadrilateral characteristics introduced by static relays are ideal (figure 3.9) [3.4]. The resistive reach can in this case be set independent of the zone reach in X-direction. Acceptable arc compensation can therefore be reached even with very short lines or cables.

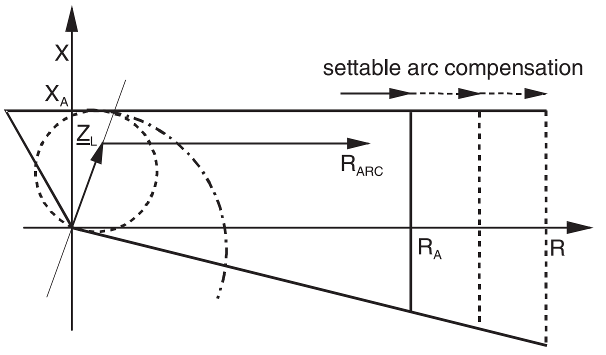


Figure 3.9
Quadrilateral tripping characteristic

Phase comparator

In analogue static technology, distance measurement is based on phase comparison. The sinusoidal signals of the phasors $\Delta\underline{U}$ and $\underline{U}_{\mathrm{ref}}$ are changed to square waves. By means of a comparator, the co-incidence (overlapping) of the squared signals is monitored. Figure 3.10 shows this for the examples of a MHO-circle and a quadrilateral. $\underline{Z}_{\mathrm{R}}$ is in both cases the set zone reach (relay impedance).

The MHO-circle is produced by measuring the angle φ between $\Delta\underline{U}$ and the short-circuit voltage $\underline{U}_{\mathrm{SC}}$. At the circumference this angle is 90 degrees corresponding to the pick-up value (coincidence limit angle $\varphi_{\mathrm{lim.}}$). Short circuit impedances inside the circle result in larger angles, i.e. longer coincidence, and consequently tripping.

The quadrilateral requires two measurements because the closed operating area is composed of a distance angle and a directional angle. The shown distance angle results from an angle measurement between a reference phasor $\underline{U}_{\mathrm{ref}}$ and the difference phasor $\Delta\underline{U}$.

Numerical relays utilise a particular algorithm to compute the fault impedance (X- and R-value) from the measured current and voltage. The result is then mathematically compared with the borders of the parameterised pick-up characteristic. Thereby it is possible to implement almost any shape and optimised characteristics, as referred to hereunder.

For circle characteristics the angle measurement between phasors is further used as criterion, but the phasors are now calculated numerically by orthogonal filters (e.g. Fourier-filter). The angle is determined by calculation of the phase shift.

3.1.5 Directional fault discrimination

On feeders with in-feed at both sides (e.g. ring network), the protection must be able to identify whether a fault is in the forward or reverse direction, to prevent reverse faults that are not on the protected feeder, from causing incorrect tripping.

The determination of direction can be shown in the current-voltage diagram as well as in the impedance plane (figure 3.11).

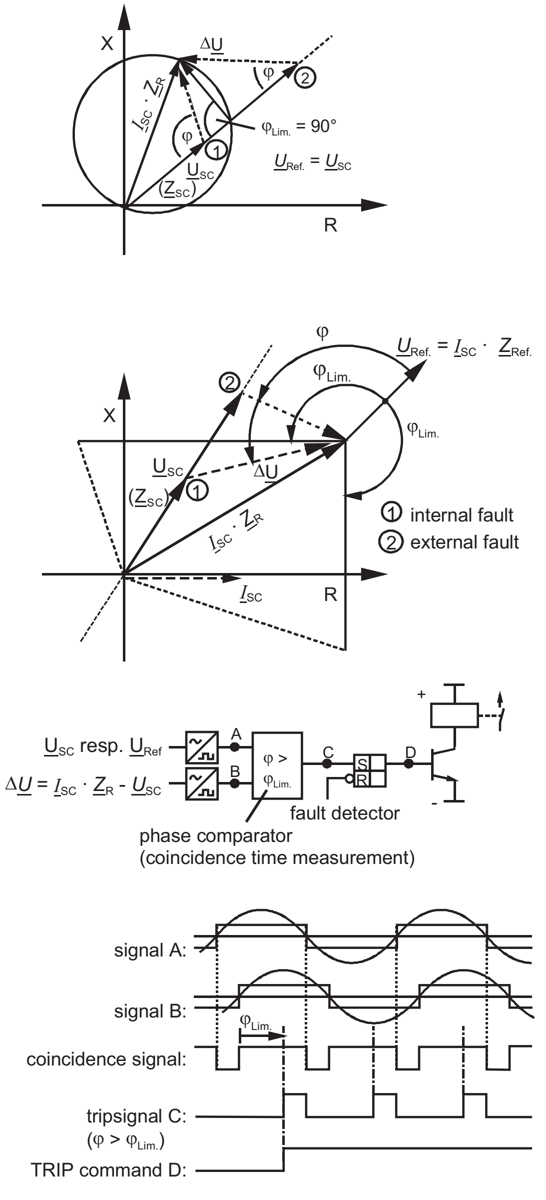
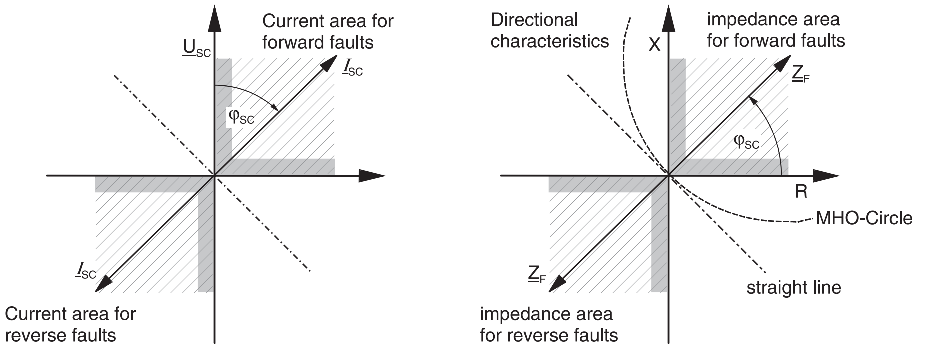


Figure 3.10
Phase comparison distance measurement (coincidence logic)

In the case of faults in the forward direction, the current flows forward into a short circuit loop made up of inductance and resistance, i.e. with the chosen phase rotation notation the current is lagging the voltage as shown in figure 3.11a, provided that the definition and connection of the measured signals to the relay are the same. The angle φ_{SC} is above 80° on EHV overhead lines, and may be below 20° on cables. The angle may even be 0° in the extreme case of a close-in short-circuit with arc resistance.[1]

[1] The special conditions existing on series compensated lines will be discussed in paragraph 3.5.7.



a) current /voltage diagram b) impedance plane

Figure 3.11 Directional fault discrimination

If the fault is in the reverse direction, the current is reversed i.e. it appears to be rotated by approximately 180° in comparison to the current which flows during a fault in the forward direction.

This current reversal also results in an impedance reversal i.e. the fault impedance lies in the 3^{rd} quadrant for the fault in reverse direction. Using this phenomenon, a direction decision can be based on the measurement of the angle between the current and voltage. The measuring circuit of conventional relays was constructed in such a manner that the directional characteristic was a straight line in the voltage or impedance plane.

With numerical relays a similar determination of the fault direction is possible, by analysing the sign of the computed fault impedances.

It has further to be considered that the conductance circle (figure 3.5) and the MHO-circle (figure 3.6b) are inherently directional, i.e. a separate directional measurement is not necessary in these cases.

The directional determination method referred to, utilises the voltage in the short-circuited loop. This method has the disadvantage that for close-in faults directly in front of or behind the relay location, no direction measurement is possible, because the voltage may in theory be equal to zero. Conventional relays of this type therefore have a so-called “dead zone” for short circuit voltages below approximately 0.1 V.

The utilisation of measured voltages from the unfaulted phases was already introduced with mechanical and analogue static relays for HV and EHV applications. In this case a voltage that is not affected by the fault is used as a substitute (cross-polarisation).

For example, the phase to phase voltage L2-L3 is used for a phase L1 to ground fault. Naturally a corresponding angle compensation must be implemented by the relay in this case. For the three-phase fault, where all voltages are affected by the fault, the voltage prior to the fault, which is stored in a voltage memory, is used. To achieve this, analogue relays had to utilise a complex voltage memory (resonant circuit), and this was therefore only used for the protection of EHV circuits.