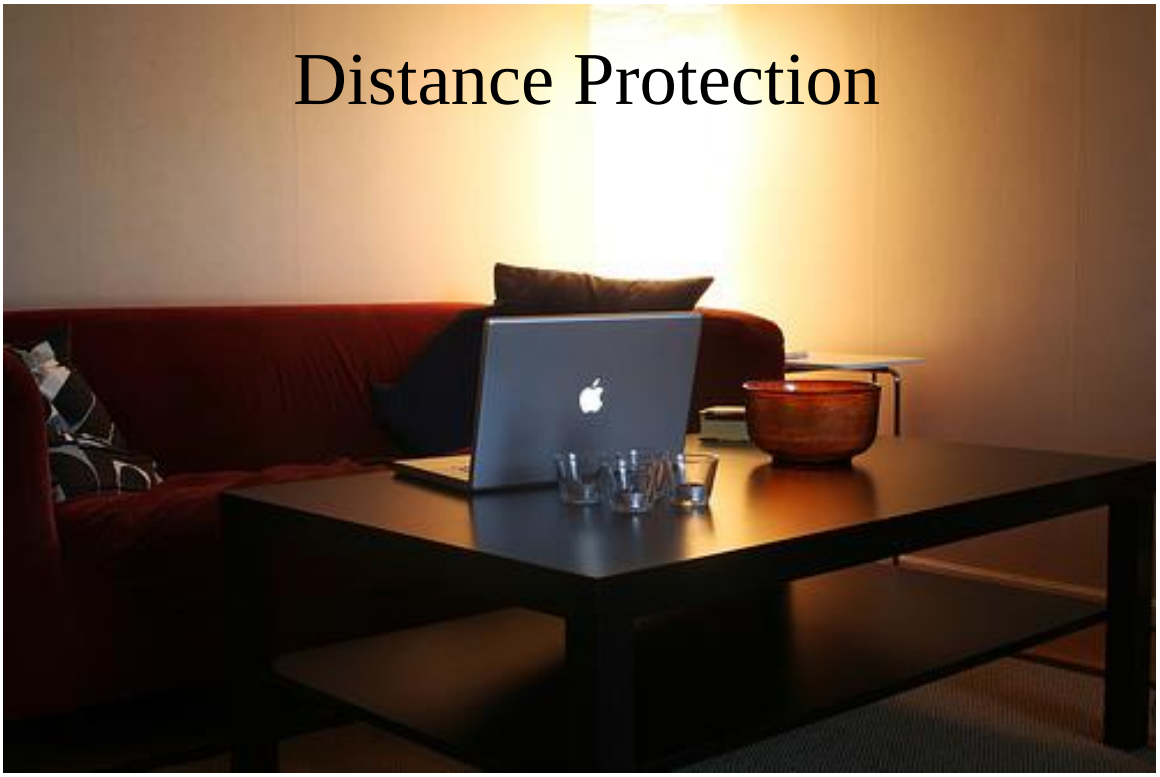


Distance Protection

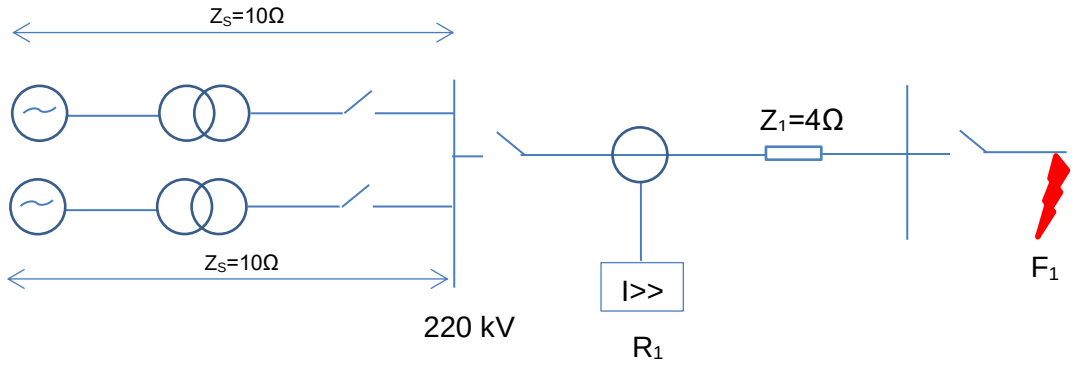
By

Velimir Lackovic, Electrical Engineer

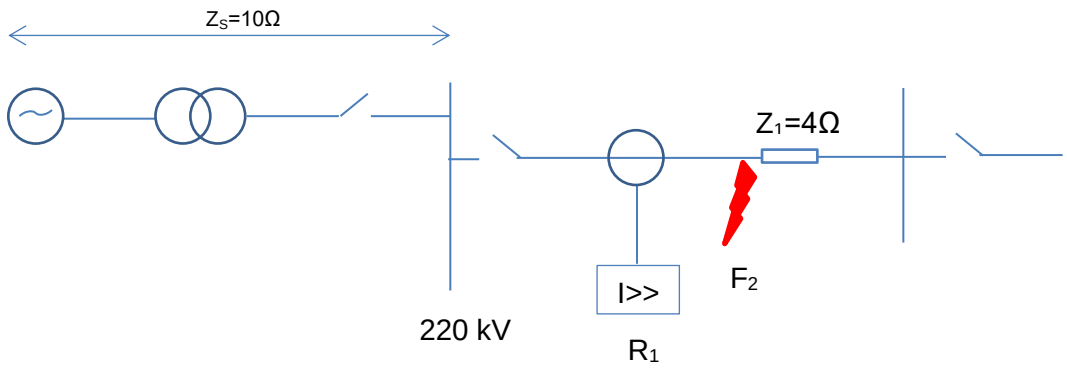
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Distance Protection

Combination of fast fault clearance with selective operation of protection element is the main objective for the protection of electrical power systems. To reach these demands, high-speed protection arrangements for electric transmission and distribution networks that are appropriate for use with the automatic reclosure of circuit breakers are under constant research. Distance protection, is a non-unit protection arrangement providing significant financial and technical benefits. Unlike phase and neutral overcurrent protection arrangements, the key benefit of distance protection is that its short circuit current coverage of the protected element is almost autonomous of source impedance changes. This principle is shown in Figure 1. It can be noted that overcurrent protection cannot be used satisfactorily.



$I_{F1} = \frac{220\times10^3}{\sqrt{3}\times(5+4)} = 14113\ A$ - Relay R_1 setting > 14113 A



$I_{F2} = \frac{220 \times 10^3}{\sqrt{3} \times 10} = 12702\ A$ - Relay R_1 setting > 12702 A

Figure 1. Benefits of distance over overcurrent protection (Relay current setting <12702 A and >14113 A.

This is not practical, overcurrent protection relay not appropriate. Distance or unit protection is preferred.

Distance protection is relatively simple to use and it can be quick in service for short circuits happening along most of a protected elements. It can also provide primary and remote back-up functions in a single operating arrangement. It can simply be adjusted to make a unit protection arrangement when used with a communication link. In this arrangement it is eminently applicable for usage with high-speed auto-reclosing, for the protection of major transmission circuits.

DISTANCE RELAY FOUNDATIONS

Since the impedance of a transmission circuit is relative to its length, for distance measure it is suitable to use a relay able to measure the impedance of a circuit up to a present point (the reach point). Such a protection relay is known as a distance protection relay and is made to function only for faults happening between the protection relay location and the chosen reach point, therefore providing discrimination for short circuits that may happen in different line portions.

The fundamental rule of distance protection includes the division of the voltage at the relaying point by the measured current. The calculated impedance is equated with the reach point impedance. In the case the measured impedance is lower than the reach point impedance, it is presumed that a fault is on the circuits between the relay and the reach point. The reach point of a protection relay is the point along the transmission line impedance locus that is crossed by the boundary feature of the protection relay. Since this depends on the ratio of voltage and current and the phase angle between them, it may be shown on an R/X graph. The loci of electrical power system impedances as detected by the protection relay during faults, power swings and load changes may be shown on the same graph. The service of the protection relay in the presence of electrical system faults and disturbances may be examined, using this method.

RELAY OPERATION

Distance protection relay operation is expressed in terms of reach exactness and operating time. Reach exactness is a comparison of the real ohmic reach of the protection relay under real circumstances with the protection relay setting value in ohms. Reach exactness is especially dependant on the level of voltage shown to the protection relay under fault period. The impedance measuring methodologies used in special relay arrangement also have an influence.

Functioning times can change with short circuit current, with short circuit position relative to the protection relay setting, and with the point on the voltage wave at which the short circuit happens. Depending on the measuring processes used in a specific relay arrangement, measuring signal transient errors, such as those made by capacitor voltage transformers or saturating CTs, can adversely slow relay function for short circuit currents close to the reach point. It is typical for electromechanical and static distance protection relays to claim both maximum and minimum functioning times. Nevertheless, for modern digital or numerical distance protection relays, the change between these is negligible over a wide range of electrical system operating states and fault locations.

ELECTROMECHANICAL/STATIC DISTANCE PROTECTION RELAYS

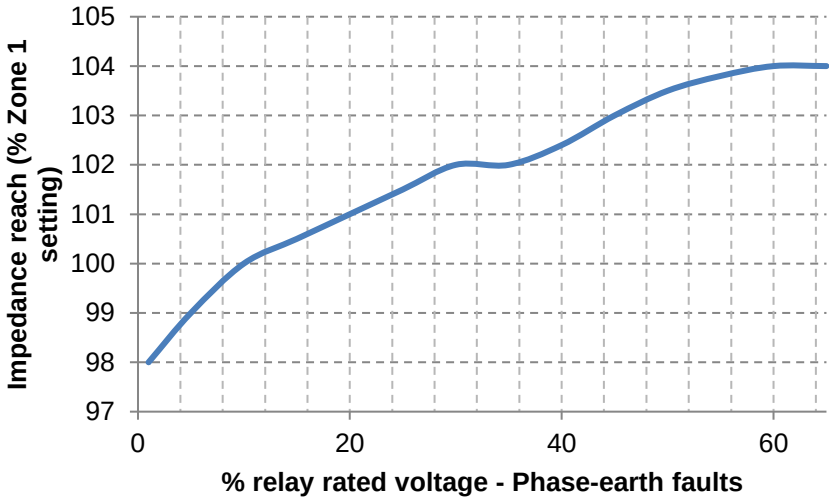
With electromechanical and static protection relay arrangements, the magnitude of input quantities especially determined both reach exactness and functioning time. It was accustomed to show data on relay operation by voltage/reach curves, as presented in Figure 2, and servicing time/fault location curves for different values of electrical system impedance ratios (S.I.R.s) as presented in Figure 3, where:

$$S.I.R = \frac{Z_s}{Z_L}$$

And

Z_S – electrical system source impedance behind the relay points

Z_L – electrical line impedance equivalent to protection relay reach setting



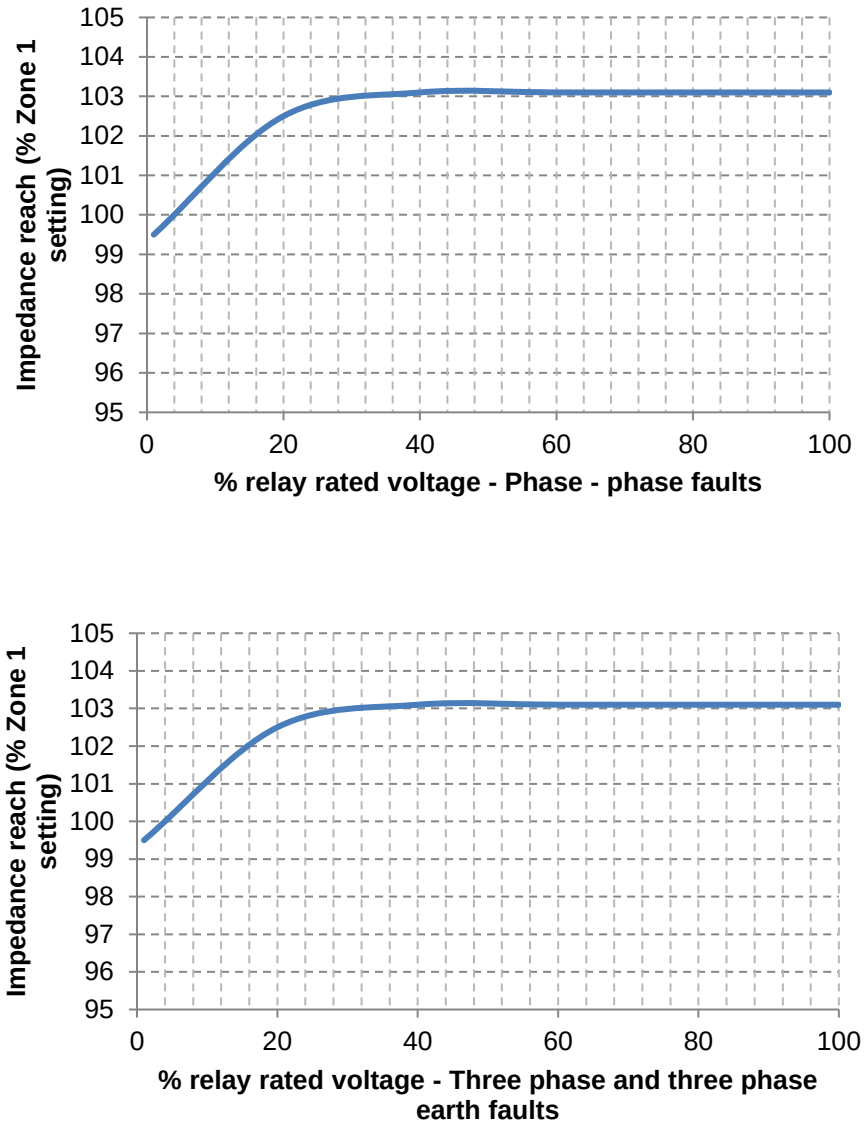
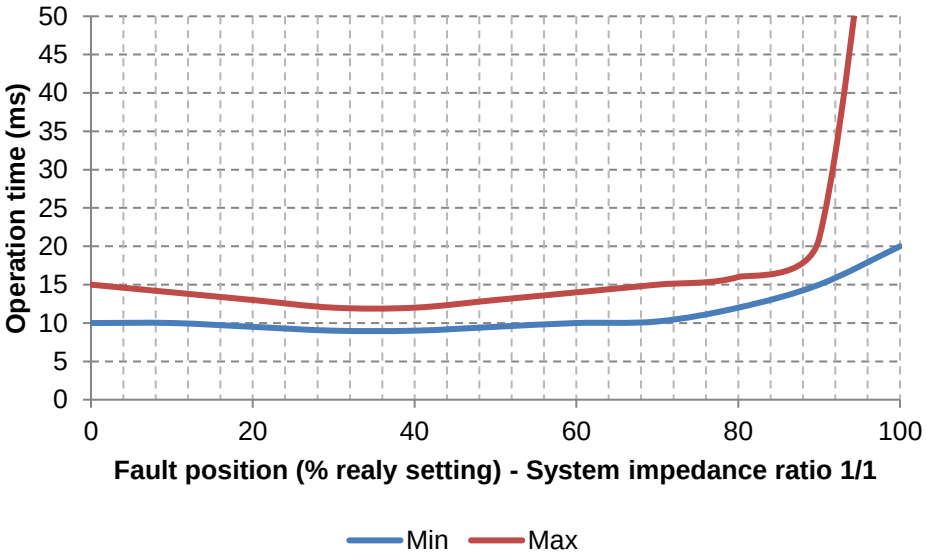


Figure 2. Common impedance reach exactness characteristics for Zone 1



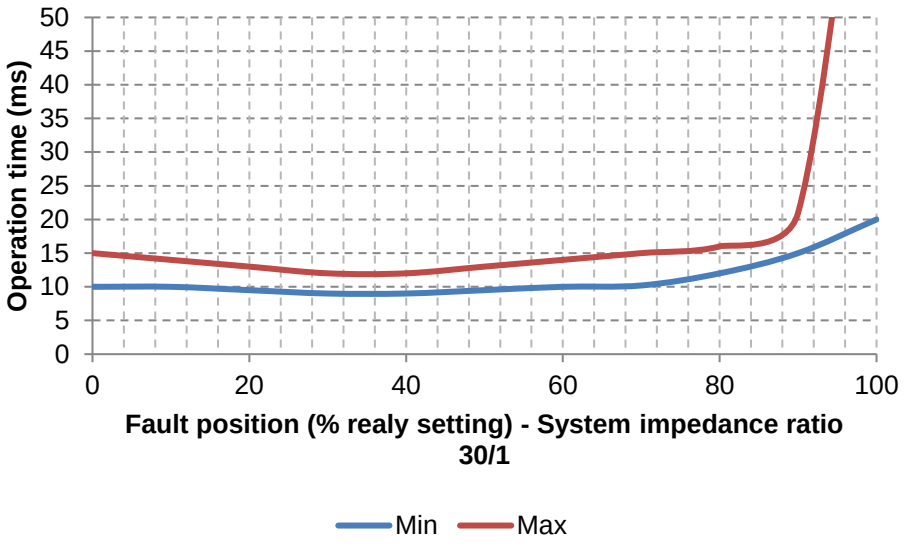
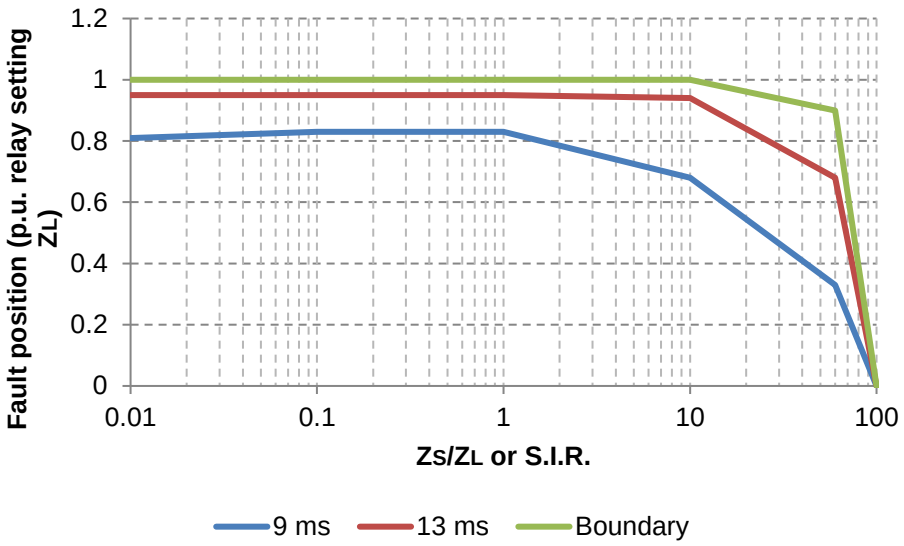


Figure 3. Common functioning time characteristics for Zone 1 line-line faults

Instead the above data was mixed in a family of contour curves, where the short circuit current location given as a percentage of the protection relay setting is presented against the source to line impedance ratio, as shown in Figure 4.



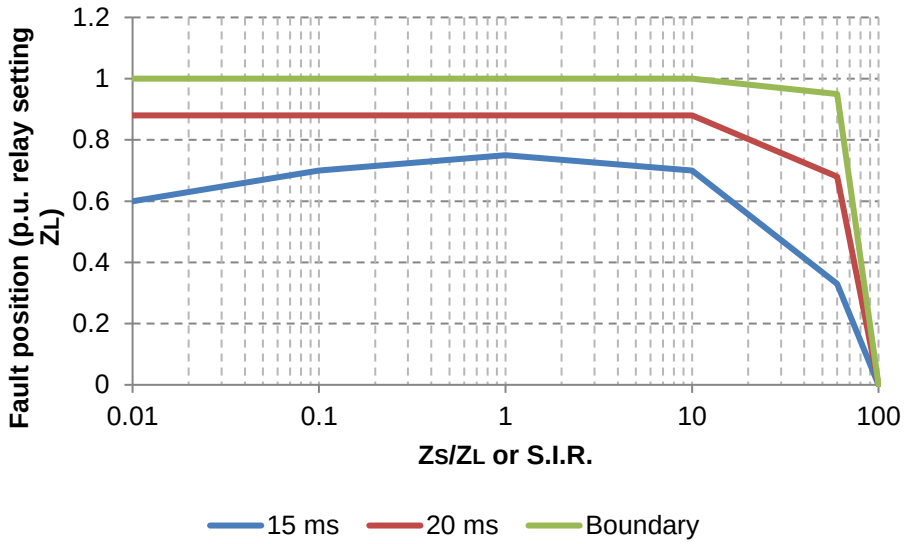


Figure 4. Common function-time contours (a) Zone 1 line-line fault: minimum performance times (b) Zone 1 line-line fault: maximum performance times

DIGITAL/NUMERICAL DISTANCE PROTECTION RELAYS

Digital/Numerical distance protection relays usually have more coherent performance times. The best transmission-class protection relays can reach sub-cycle functioning, and the available digital filtering processes guarantee optimum service under adverse waveform circumstances or for boundary fault conditions.

RELATIONSHIP BETWEEN RELAY VOLTAGE AND Z_S/Z_L RATIO

A unique, generic, equivalent circuit, as presented in Figure 5, may correspond to any short circuit current condition in a three-phase electrical power system. The voltage V enforced to the impedance loop is the open circuit voltage of the electrical power system. Point R corresponds to the relay position; I_R and V_R are the current and voltage sensed by the relay.

The impedances Z_s and Z_L are depicted as source and transmission line impedances because of their location in relation to the relay location. Source impedance Z_s is a quantity of the short circuit current level at the relaying location. For shot circuit currents involving ground it is dependent on the technique of electrical system grounding behind the relaying location. Line impedance Z_L is a quantity of the impedance of the protected region. The voltage V_R utilized to the protection relay is, hence, I_RZ_L. For a short circuit current at the reach point, this may be instead conveyed

in terms of source to transmission line impedance ratio Z_S/Z_L applying the following equation:

$$V_R = I_R Z_L$$

Where

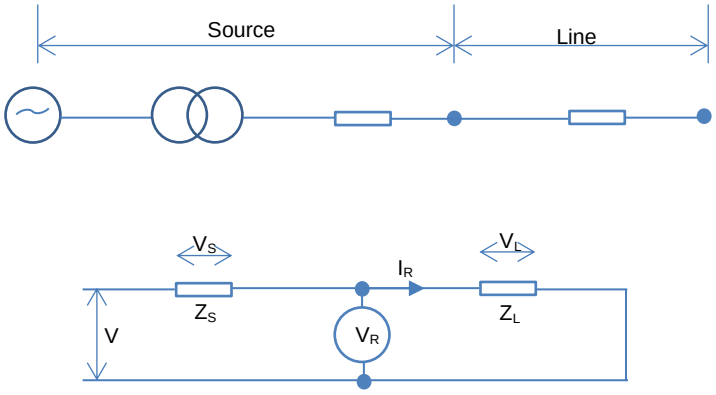
$$I_R = \frac{V}{Z_S + Z_L}$$

Hence,

$$V_R = \frac{Z_L}{Z_S + Z_L} V$$

Or

$$\mathrm{V_R} = \frac{1}{\left(\frac{Z_S}{Z_L}\right)+1}\mathrm{V} \qquad (1)$$



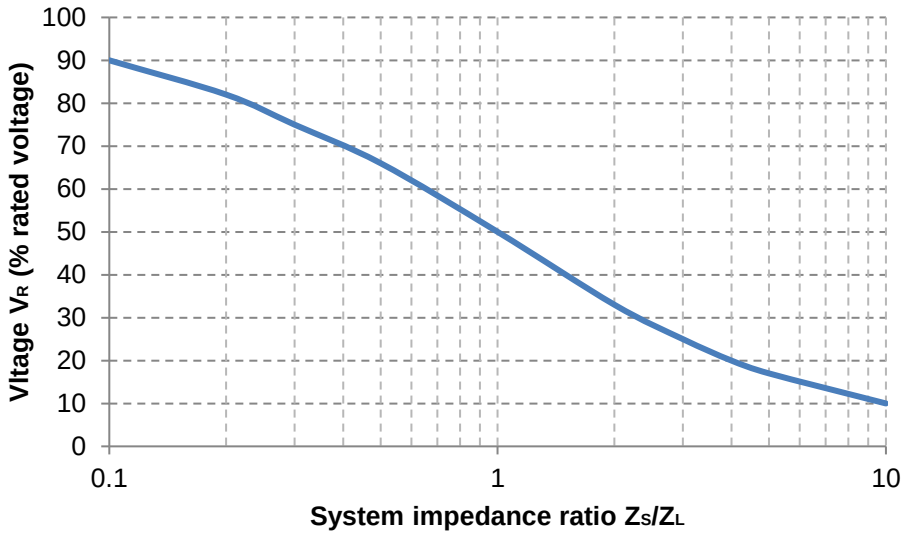


Figure 5. Link between source to transmission line ratio and protection relay voltage (a) Electrical power system arrangement (b) Change of protection relay voltage with electrical system source to transmission line impedance ratio

The above universal relationship between V_R and Z_S/Z_L, presented in Figure 5, is true for all cases of short circuit currents given a few elementary rules are kept. These rules are:

- For line faults, V_Δ is the line-line source voltage and Z_S/Z_L is the positive sequence source to transmission line impedance ratio. V_R is the line-line protection relay voltage and I_R is the line-line protection relay current, for the faulted lines

$$V_R = \frac{1}{\left(\frac{Z_S}{Z_L}\right)+1} V_\Delta \qquad (2)$$

- For ground short circuit currents, $V_{l\text{-}n}$ is the line-neutral source voltage and Z_S/Z_L, is a composite ratio taking the positive and zero sequence impedances. V_R is the line-neutral protection relay voltage and I_R is the protection relay current for the faulted line

$$V_R = \frac{1}{\left(\frac{Z_S}{Z_L}\right)\left(\frac{2+p}{2+q}\right)+1} V_{l-n} \qquad (3)$$

Where:

$$Z_S = 2Z_{S1} + Z_{S0} = Z_{S1}(2 + p)$$

$$Z_L = 2Z_{L1} + Z_{L0} = Z_{L1}(2 + q)$$

And

$$p = \frac{Z_{S0}}{Z_{S1}}$$

$$q = \frac{Z_{L0}}{Z_{L1}}$$

VOLTAGE LIMIT FOR PRECISE REACH POINT MEASUREMENT

The power of a distance protection relay to precisely assess reach point fault is dependent on the minimum voltage at the protection relay position under this condition. This voltage, that is dependent on the protection relay arrangement, can also be expressed in terms of an equivalent maximum Z_S/Z_L or S.I.R. Distance protection relays are made so that, given the reach point voltage standard is reached, any increased measuring errors for short circuits closer to the protection relay will not stop protection relay performance. Most protection relays are manufactured with healthy line voltage polarisation and/or memory voltage polarisation. The prime use of the protection relay polarising voltage is to make sure correct protection relay directional response for close-up short circuit currents, in the forward or reverse direction, where the fault-loop voltage sensed by the protection relay may be very low.

DISTANCE PROTECTION ZONES

Careful choice of the reach settings and operation times for the different zones of measurement allows proper coordination between distance protection relays on a electric power system. Fundamental distance protection will contain instantaneous directional Zone 1 relay protection and one or more time-delayed zones. Common reach and time settings for a 3-zone distance relay protection are presented in Figure 6. Digital and numerical distance protection relays may have up to five or six protection zones, some set to sense in the reverse direction. Common settings for three forward-looking zones of basic distance relay protection are shown in the following paragraphs. To find out the settings for a specific protection relay arrangement or for a specific

distance tele-protection arrangement, involving end-to-end signalling, the protection relay producer's suggestions and manuals should be consulted.

ZONE 1 PROTECTION SETTING

Electromechanical/static protection relays typically have a reach setting of up to 80% of the protected transmission line impedance for instantaneous Zone 1 protection. For digital/numerical distance protection relays, settings of up to 85% may be adequate. The obtained 15-20% safety margin assures that there is no possibility of the Zone 1 protection over-reaching the protected transmission circuit due to errors in the current and voltage transformers, inaccuracies in transmission line impedance information given for setting needs and errors of protection relay setting and measurement. Otherwise, there would be improper discrimination with fast functioning relay protection on the following transmission line section. Zone 2 of the distance relay protection has to cover the remaining 15-20% of the transmission line.

ZONE 2 PROTECTION SETTING

To assure complete coverage of the transmission line with provision for the sources of error already presented in the previous paragraph, the reach protection setting of the Zone 2 protection need to be at least 120% of the protected transmission line impedance. In many usages it is typical practice to set the Zone 2 reach to be same to the protected transmission line section +50% of the shortest adjacent transmission line. Where feasible, this assures that the ending maximum effective protection Zone 2 reach does not goes beyond the minimum effective protection Zone 1 reach of the adjacent transmission line protection. This eliminates the requirement to grade the protection Zone 2 time settings between upstream and downstream protection relays. In electromechanical and static protection relays, Zone 2 protection is given either by different elements or by extending the protection reach of the Zone 1 devices after a time delay that is started by a fault detector. In majority of digital and numerical protection relays, the Zone 2 devices are put in software.

Zone 2 tripping has to be time-delayed to assure grading with the primary protection relaying used to adjacent transmission circuits that fall within the Zone 2 protection reach. Hence, full coverage of a transmission line portion is achieved, with fast

clearance of short circuits in the first 80-85% of the transmission line and reasonably slower short circuit current clearance in the remaining portions of the transmission circuit.

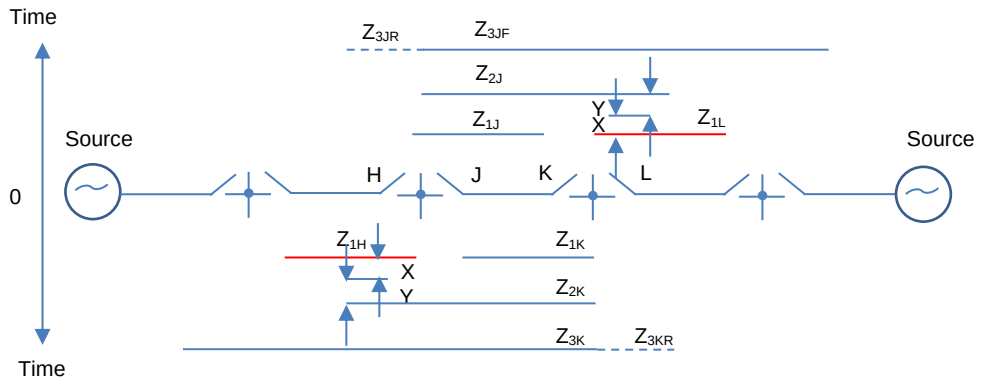


Figure 6. Common time/distance characteristics for three zone distance relay protection

Zone 1 =80-85% of protected transmission line impedance

Zone 2 (minimum)=120% of protected transmission line

Zone 2 (maximum)<Protected transmission line+50% of shortest second transmission line

Zone 3F=1.2 (protected transmission line +longest second transmission line)

Zone 3R=20% of protected transmission line

X= Circuit breaker tripping time

Y= Discriminating time

ZONE 3 PROTECTION SETTING

Remote back-up relay protection for all short circuit currents on adjacent transmission lines can be given by a third zone of relay protection that is time delayed to discriminate with Zone 2 relay protection plus circuit breaker operation time for the adjacent transmission line. Protection Zone 3 reach should be adjusted to at least 1.2 times the impedance given to the protection relay for a short circuit at the remote end of the second transmission line portion. On interconnected electrical power systems, the impact of short circuit current infeed at the remote bus will create the impedance shown to the protection relay to be much higher than the actual impedance to the short circuit and this has to be considered when setting protection Zone 3. In some electrical systems, differences in the remote bus infeed can prohibit the usage of remote back-

up protection Zone 3 but on radial distribution electrical systems with single end infeed, there should not be problems.

PROTECTION SETTINGS FOR REVERSE REACH AND OTHER ZONES

Modern digital or numerical protection relays may have extra impedance zones that can be used to give extra protection functions. For instance, where the first three protection zones are set as above, Zone 4 could be used to give back-up protection for the local bus, by using a reverse reach setting of the order of 25% of the protection Zone 1 reach. Also, one of the forward-looking protection zones (usually Zone 3) could be adjusted with a low reverse offset reach from the origin of the R/X graph, in addition to its forward reach setting. An offset impedance measurement characteristic is non-directional. One benefit of a non-directional protection zone of impedance measurement is that it is capable to function for a close-up, zero-impedance short circuit, in cases where there may be no healthy line voltage signal or memory voltage signal available to permit performance of a directional impedance zone. With the offset-zone time delay bypassed, there can be provision of 'Switch-on-to-Fault' (SOTF) protection. This is needed where there are line voltage transformers, to give fast tripping in the case of inadvertent transmission line energisation with maintenance grounding clamps left in place. Extra impedance zones may be positioned as part of a distance relay protection arrangement used together with a tele-protection signalling medium.

DISTANCE PROTECTION RELAY FEATURES

Some numerical relays measure the absolute fault impedance, and then check if operation is needed according to impedance boundaries predetermined on the R/X graph. Typical distance protection relays and numerical protection relays that emulate the impedance elements of common protection relays do not measure absolute impedance. These protection relays compare the sensed short circuit voltage with a replica voltage deduced from the short circuit current and the zone impedance setting to check if the short circuit is within zone or out-of-zone. Distance protection relay impedance comparators or algorithms which emulate typical comparators are organised in line to their polar features, the number of signal inputs they contain, and the procedure by which signal comparisons are determined. The typical types

compare either the relative amplitude or phase of two input measures to get performance features that are either straight lines or circles when printed on an R/X graphs. At each stage of distance protection relay design, the development of impedance performance features shapes and sophistication has been regulated by the present technology and the acceptable cost. Since many typical protection relays are still in operation and since some numerical protection relays emulate the processes of the typical protection relays, a brief review of impedance comparators is needed.

AMPLITUDE AND PHASE COMPARISON

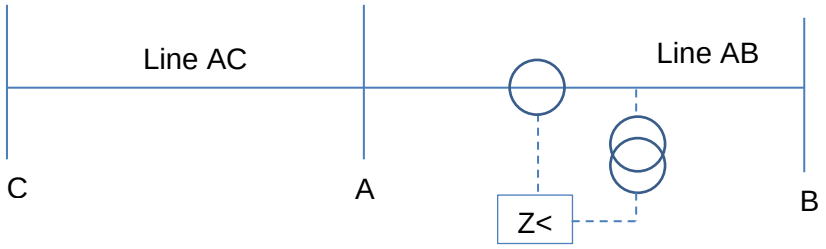
Protection relay measuring devices whose practicality is determined on the comparison of two independent measures are basically either amplitude or phase comparators. For the impedance elements of a distance protection relay, the measures being compared are the voltage and current sensed by the protection relay. There are different methodologies for completing the comparison, depending on the used technology. They differ from balanced beam (amplitude comparison) and induction cup (phase comparison) electromagnetic protection relays, even though diode and operational amplifier comparators in static-type distance protection relays, to digital sequence comparators in digital protection relays and to algorithms used in numerical protection relays.

Any method of impedance feature gettable with one comparator is also gettable with the other. The addition and subtraction of the signals for one comparator type gives the needed signals to get a similar characteristic using the other type. For instance, comparing V and I in an amplitude comparator ends in a circular impedance characteristic placed at the origin of the R/X graph. If the sum and difference of V and I are put to the phase comparator the ending result is a similar characteristic.

PLAIN IMPEDANCE CHARACTERISTIC

The pain impedance characteristic does not take into account the phase angle between the current and the voltage put to it; for this reason its impedance characteristic when printed on an R/X graph is a circle with its centre at the origin of the coordinates and of radius same to its setting in ohms. Operation happens for all

impedance quantities less than the setting, that is, for all points inside the circle. The protection relay characteristic, presented in Figure 7, is hence non-directional, and in this form would trip for all short circuit currents along the vector AL and also for all short circuits behind the bus to an impedance AM. A is the protection relaying point and RAB is the angle by which the short circuit current lags the protection relay voltage for a short circuit on the line AB and RAC is the same leading angle for a short circuit on line AC. Vector AB displays the impedance in front of the protection relay between the protection relaying point A and the end of line AB. Vector AC presents the impedance of line AC behind the protection relaying point. AL presents the reach of instantaneous protection Zone 1, set to cover 80% to 85% of the protected transmission line.



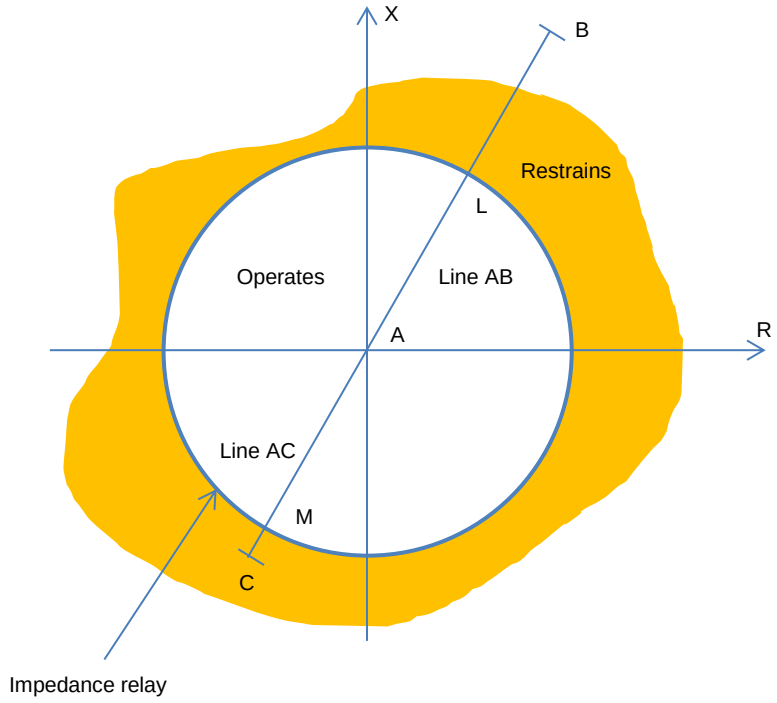


Figure 7. Plain impedance protection relay characteristic

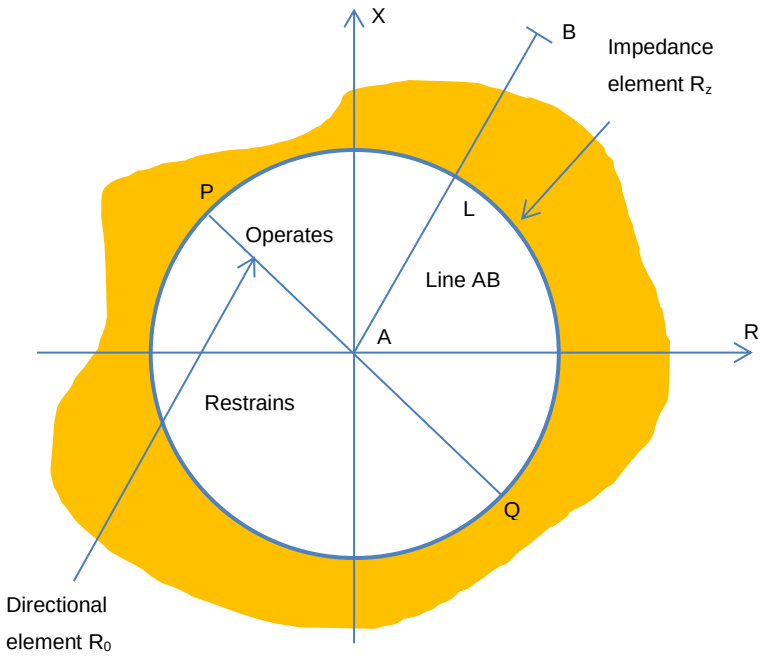
A protection relay using this characteristic has three important drawbacks:

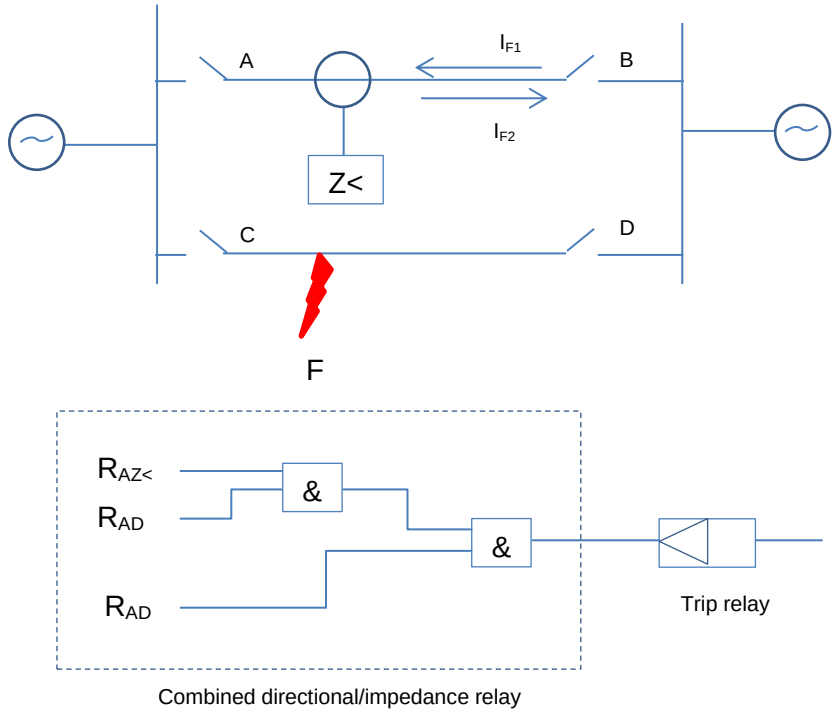
- It is non-directional; it will sense short circuits both in front of and behind the protection relaying point, and hence needs a directional device to provide it exact discrimination

- It has non-uniform short circuit resistance coverage

- It is non-resistant to power oscillations and heavy loading of a long transmission line because of the large area covered by the impedance circle

Directional control is basic discrimination measure for a distance protection relay, to make the protection relay non-responsive to short circuits outside the protected transmission line. This can be received by the addition of a separate directional control device. The impedance characteristic of a directional control device is a straight line on the R/X graph, so the mixed characteristic of the directional and impedance protection relays is the semi-circle APLQ displayed in Figure 8.





$R_{AZ<}$ - distance device at A

R_{AD} – directional device at A

Figure 8. Mixed directional and impedance protection relays (a) Characteristic of mixed directional/impedance relay (b) Example of use of directional/Impedance protection relay (c) Logic for directional and impedance protection devices at A

If a short circuit happens at F near to C on the parallel line CD, the directional unit RD at A will hold due to current I_{F1}. At the same time, the impedance element is retained from performing by the inhibiting output of unit RD. If this control is not given, the under impedance device could function prior to circuit breaker C tripping. Reversal of current through the protection relay from I_{F1} to I_{F2} when C opens could then end in incorrect operation of the healthy transmission line if the directional element RD performs before the impedance unit resets. From this example, need to address the adequate co-ordination of multiple protection relay elements to achieve reliable protection relay performance during evolving fault conditions, can be seen. In older protection relay arrangements, the type of problem to be considered was typically mentioned as one of ‘contact race’.

SELF-POLARISED MHO PROTECTION RELAY

The mho impedance element is typically known as such since its characteristic is a straight line on an admittance graph. It mixes the discriminating measures of both reach control and directional control, therefore cancelling the 'contact race' issues that may be found with separate reach and directional control devices. This is accomplished by introduction of a polarising signal. Mho impedance devices were especially attractive for financial reasons where electromechanical relay devices were used. Finally, they have been used worldwide for many years and their benefits and drawbacks are now well known. For this reason they are still implemented in the algorithms of some numerical protection relays. The characteristic of a mho impedance device, when printed on an R/X graph, is a circle whose circumference goes through the origin, as shown in Figure 9. This shows that the impedance device is inherently directional and such that it will function only for short circuits in the forward direction along line AB.

The impedance characteristic is adapted by setting Z_n, the impedance reach, along the diameter and φ, the angle of displacement of the diameter from the R axis. Angle φ is known as the Relay Characteristic Angle (RCA). The relay performs for quantities of fault impedance ZF within its characteristic. The self-polarised mho characteristic can be found using a phase comparator circuit which compares input signals S_2 and S_1 and performs whenever S_2 lags S_1 by between 90° and 270°, as presented in the voltage graph of Figure 9.

The two input signals are:

$$S_2 = V - IZ_n$$

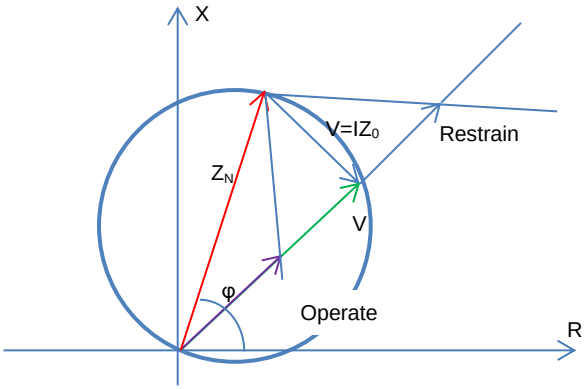
$$S_1 = V$$

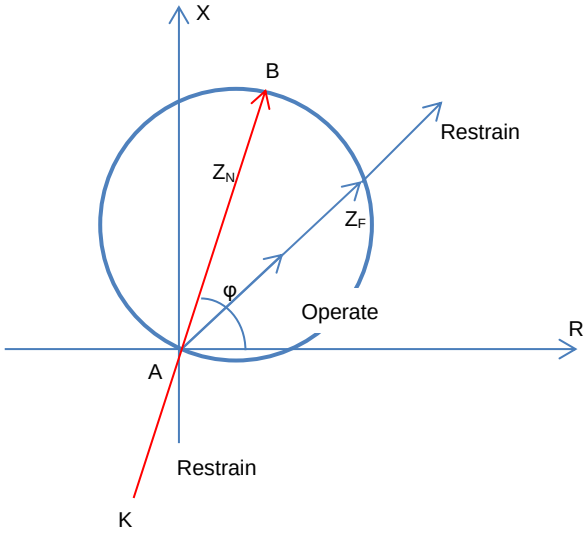
where:

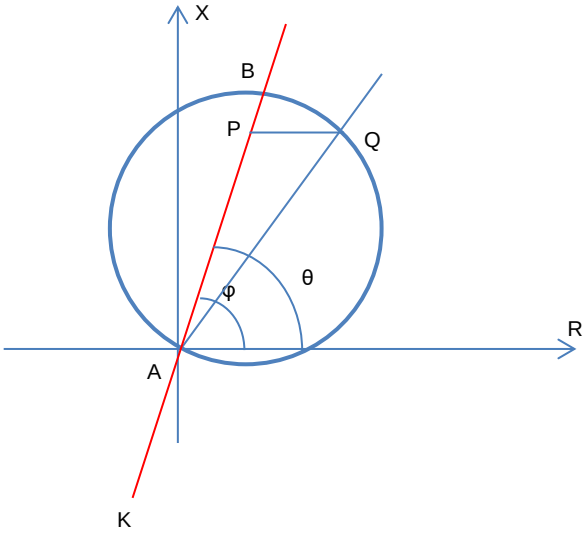
V - fault voltage from VT secondary

I - fault current from CT secondary

Z_n - impedance setting of the zone







AQ – Relay impedance setting

φ – Relay characteristic angle setting

AB – Protected transmission line

PQ – Arc resistance

θ – Line angle

Figure 9. Mho protection relay characteristics (a) Phase comparator inputs (b) Mho impedance characteristics (c) Increased arc resistance coverage

The characteristic shown in Figure 9 (a) can be translated to the impedance plane of Figure 9(b) by dividing each voltage by I. The impedance reach changes with short circuit angle. As the protected transmission line is made up of resistance and inductance, its short circuit current angle will depend upon the relative quantities of R and X at the power system operating frequency. Under an arcing fault condition, or ground fault involving extra resistance, such as tower footing resistance, the value of the resistive element of short circuit impedance will raise to change the impedance angle. Thus a protection relay having a characteristic angle same to the transmission line angle will under reach under resistive short circuit conditions. Some engineers set the RCA less than the transmission line angle, so that it is feasible to accept a small quantity of short circuit resistance without causing under-reach. Nevertheless, when setting the protection relay, the difference between the line angle θ and the protection relay characteristic angle Ø has to be known. The resulting characteristic is presented in Figure 9 where GL represents the length of the protected transmission line. With the angle Ø set less than θ, the actual quantity of protected transmission line, AB, would be same to the protection relay setting quantity AQ multiplied by cos(θ-Ø). Hence the needed protection relay setting AQ is determiend by:

$$AQ = \frac{AB}{\cos(\theta - \varphi)}$$

Due to the physical nature of an electric arc, there is a non-linear relationship between arc voltage and arc current, which ends in a non-linear resistance. Using the empirical equation the estimated quantity of arc resistance can be determined as:

$$R_a = \frac{28710}{I^{1.4}} L \qquad (4)$$

where:

R_a = arc resistence (ohms)

L = length of arc (metres)

I = arc current (A)

On long overhead transmission lines installed on steel towers with overhead ground wires the impact of arc resistance can typically be neglected. The impact is predominant on short overhead transmission lines and with short circuit currents below 2000A (i.e. minimum plant condition), or if the protected transmission line is of wood-pole construction without ground wires. In the second case, the ground short circuit resistance decreases the effective ground-fault reach of a 'mho' protection Zone 1 device to such an extent that the majority of short circuits are sensed in Zone 2 time.

This issue can typically be solved by using a protection relay with a cross-polarised mho or a polygonal characteristic. Where an electrical power system is resistance-grounded, it should be noted that this does not have to be treated with regard to the protection relay settings other than the effect that decreased short circuit current may have on the value of arc resistance sensed. The grounding resistance is in the source behind the protection relay and only changes the source angle and source to transmission line impedance ratio for ground faults. Hence, it would be considered only when examining protection relay operation in terms of system impedance ratio.

OFFSET MHO/LENTICULAR CHARACTERISTICS

Under close up short circuit conditions, when the protection relay voltage drops to zero or near-zero, a protection relay using a self-polarised mho characteristic or any other shape of self-polarised directional impedance characteristic may not function when it is needed to do so. Processes of covering this situation include the use of non-directional impedance characteristics, such as offset mho, offset lenticular, or cross-polarised and memory polarised directional impedance characteristics. If current bias is used, the mho characteristic is shifted to embrace the origin, so that the measuring

device can function for close-up short circuits in both the forward and the reverse directions. The offset mho protection relay has two main usages:

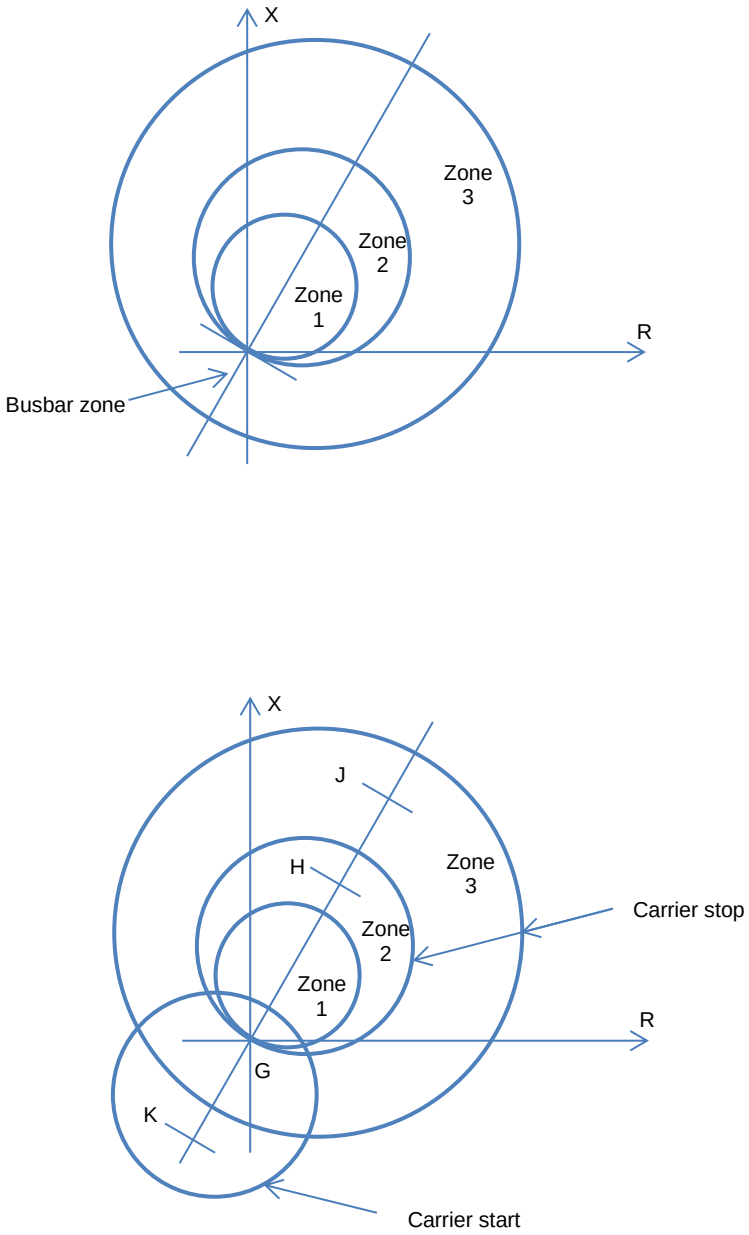


Figure 10. Common usage for the offset mho protection relay (a) Bus zone back-up using an offset mho protection relay (b) Carrier starting in distance blocking arrangements

THIRD PROTECTION ZONE AND BUSBAR BACK-UP PROTECTION ZONE

In this usage it is applied in conjunction with mho measuring devices as a short circuit detector and/or protection Zone 3 measuring device. So, with the reverse reach set up to extend into the bus protection zone, as presented in Figure 10, it will give back-up protection for bus short circuits. This facility can be given with quadrilateral characteristics. A further advantage of the protection Zone 3 usage is for Switch-on-to-Fault (SOTF) protection, where the protection Zone 3 time delay would be by-passed for a short period shortly following line switching to provide quick clearance of a short circuit anywhere along the protected transmission line.

CARRIER STARTING DEVICE IN DISTANCE PROTECTION ARRANGEMENTS WITH CARRIER BLOCKING

If the offset mho device is utilized for starting carrier signalling, it is arranged as presented in Figure 10. The carrier is transferred if the short circuit is external to the protected transmission line but inside the reach of the offset mho protection relay, to stop accelerated operation of the second or third zone protection relay at the remote station. Transmission is reverted for internal short circuits by operation of the local mho measuring devices, which provide high-speed fault clearance by the local and remote end circuit breakers.

USAGE OF LENTICULAR CHARACTERISTIC

There is a possibility that the offset mho protection relay displayed in Figure 11 may trip under maximum load transfer conditions if protection Zone 3 of the protection relay has a big reach setting. A great protection Zone 3 reach may be needed to give remote back-up protection for short circuits on the adjacent circuit. To avert this, a shaped mode of characteristic may be utilized, where the resistive coverage is limited. With a 'lenticular' characteristic, the aspect ratio of the lens $\left(\frac{a}{b}\right)$,a is changeable, allowing it to be set to give the maximum short circuit resistance coverage consistent with nonoperation under maximum load transfer situations. Figure 11 presents how the lenticular characteristic can allow greater degrees of transmission line loading than offset mho and plain impedance characteristics. Decrease of load impedance from Z_{D3} to Z_{D1} will relate to same rise in load current.

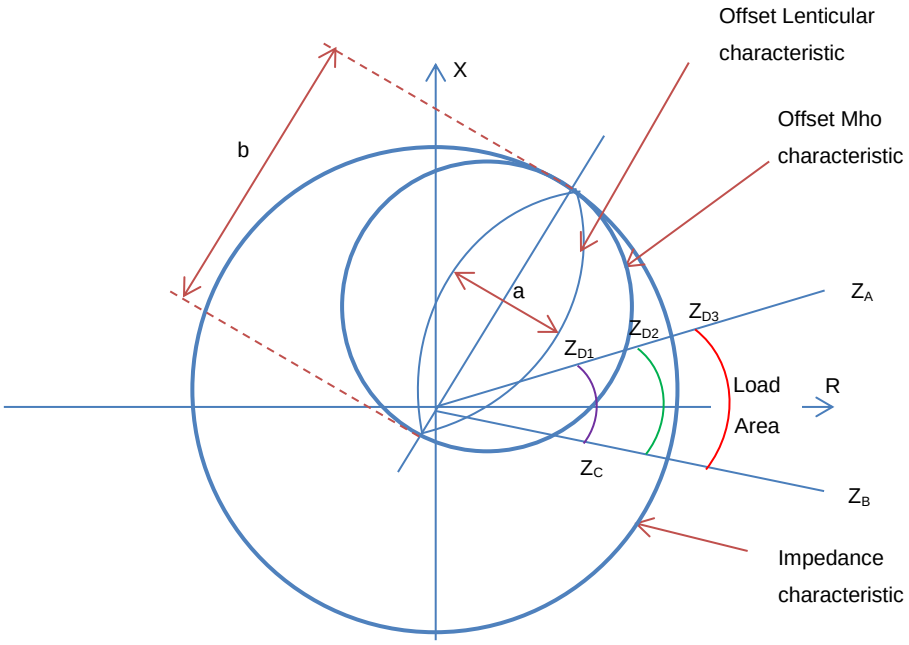


Figure 11. Minimum load impedance allowed with lenticular, offset mho and impedance protection relays

It can be noted in Figure 11 how the load area is fixed according to a minimum impedance arc, limited by straight lines which exhale from the origin, 0. Modem numerical protection relays usually do not utilize lenticular characteristic shaping, but alternatively utilize load encroachment (load blinder) sensing. This makes possible a full mho characteristic to be utilized, but with tripping stopped in the region of the impedance plane known to be frequented by load (Z_A-Z_B-Z_C-Z_D).

FULLY CROSS-POLARISED MHO CHARACTERISTIC

The previous paragraph presented how the non-directional offset mho characteristic can inherently trip for close-up zero voltage short circuits, where there would be no polarising voltage to grant operation of a plain mho directional device. One way of making sure the correct mho device response for zero-voltage short circuits is to add a percentage of voltage from the healthy line(s) to the main polarising voltage as a substitute phase reference. This method is known as cross-polarising, and it has the benefit of keeping and increasing the directional features of the mho characteristic. By

the use of a phase voltage memory techniques, that gives several cycles of pre-short circuit voltage reference during a short circuit, the cross-polarisation method is also efficient for close-up three-phase short circuits. For this type of short circuit, no healthy line voltage reference is usable.

Early memory system techniques were established on tuned, resonant circuits, but issues happened when used in power networks where the power system operating frequency could change. Sophisticated digital or numerical elements can provide a synchronous line reference for changes in power system frequency before or during a short circuit. Drawback of the self-polarised plain mho impedance characteristic, when used on overhead transmission circuits with large impedance angles, is that it has fixed coverage of arc or fault resistance. The issue is worsened in the situation of short transmission circuits, since the needed protection Zone 1 ohmic setting is low. The degree of the resistive coverage provided by the mho circle is linked to the forward reach setting. Therefore, the ending resistive coverage may be too small in comparison to the anticipated quantities of fault resistance. One extra advantage of using cross-polarisation to a mho impedance device is that its resistive coverage will be improved. This impact is presented in Figure 12, in the situation where a mho device has 100% cross-polarisation. With cross-polarisation from the healthy line(s) or from a memory system element, the mho resistive expansion will happen during a balanced three-line short circuit as well as for unbalanced short circuits. The expansion will not happen under load conditions, when there is no phase shift between the measured voltage and the polarising voltage. The degree of resistive reach increase depends on the ratio of source impedance to protection relay reach (impedance) setting as can be deduced by reference to Figure 13.

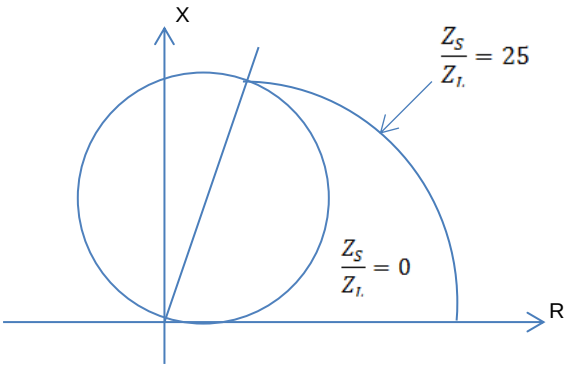
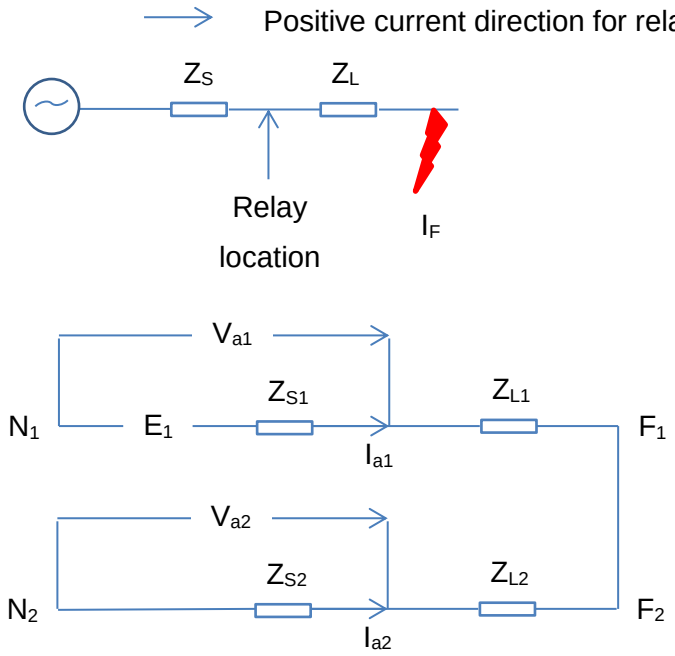


Figure 12. Fully cross-polarized mho relay characteristic with variations of ZS/ZL ratio



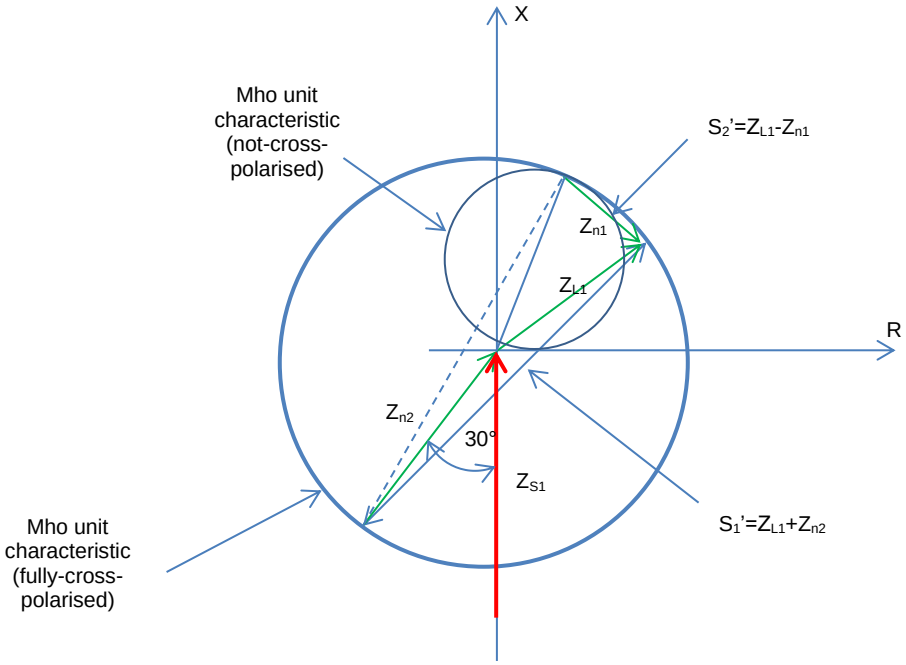


Figure 13. Diagram of enhancing protection relay resistive coverage for fully cross-polarised characteristic

It have to be highlighted that the evident extension of a fully cross-polarised impedance characteristic into the negative reactance quadrants of Figure 13 does not mean that there would be trip for reverse short circuits. With cross-polarisation, the relay characteristic extends to cover the beginning of the impedance graph for forward short circuits only. For reverse short circuits, the impact is to omit the beginning of the impedance graph, thereby making sure adequate directional responses for close-up forward or reverse short circuits. Fully cross-polarised characteristics have now greatly been replaced, due to the trend of comparators linked to healthy line to trip under heavy short circuit circumstances on another line. This is of no effect in a switched distance protection relay, where a single comparator is linked to the adequate short circuit loop impedance by starting units before measurement starts. Nevertheless, modern protection relays provide independent impedance measurement for each of the three ground-fault and three line-fault loops. For these protection relays, mal-operation of live lines is unwanted, particularly when single-pole tripping is needed for single-line short circuits.

PARTLY CROSS-POLARISED MHO CHARACTERISTIC

Where a dependable, independent technique of faulted line selection is not given, a modern non switched distance protection relay may only use a comparatively small percentage of cross polarisation. The picked out level has to be enough to give dependable directional control in the presence of CVT transients for close-up short circuits, and also achieve dependable faulted line selection. By using only partial cross-polarisation, the drawback of the fully cross-polarised characteristic are averted, while still keeping the benefits. Figure 14 presents a common characteristic that can be found using this method.

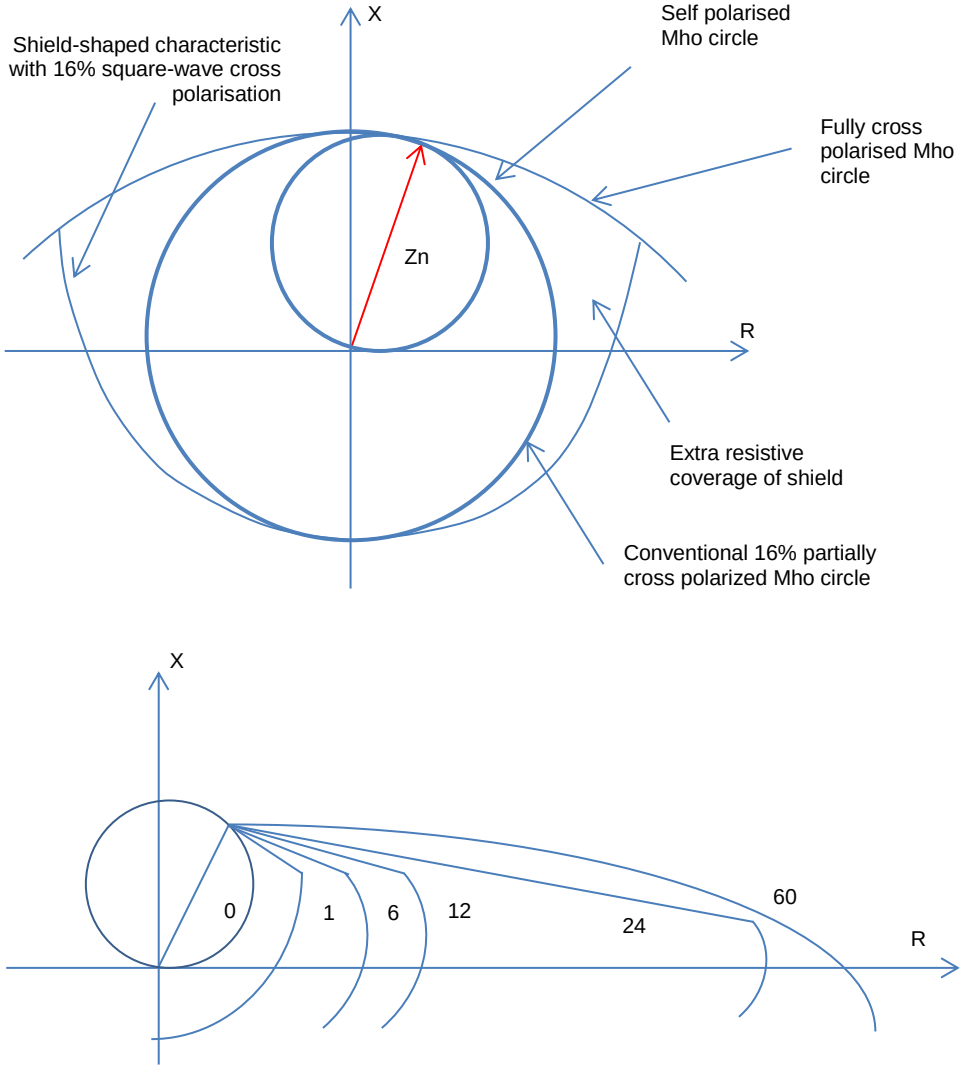


Figure 14. Partially cross-polarised characteristic with “shield” shape (a) comparison of polarized characteristics made for S.I.R.=6 (b) Resistive enlargement of shaped partly cross-polarised Mho with increasing values of S.I.R.

QUADRILATERAL CHARACTERISTIC

This shape of polygonal impedance characteristic is presented in Figure 15. The characteristic is given with forward reach and resistive reach settings that are independently changeable. Hence, it gives better resistive coverage than any mho-type characteristic for short transmission lines. This is particularly correct for ground fault impedance measurement, where the arc resistances and short circuit resistance to ground contribute to the greatest values of fault resistance. To avert significant errors in the protection zone reach precision, it is typical to enforce a maximum resistive reach in terms of the protection zone impedance reach. Suggestions about this can typically be found in the technical protection relay brochures and manuals. Quadrilateral devices with plain reactance reach lines can bring in reach error issues for resistive ground short circuits where the angle of total short circuit current differs from the angle of the current sensed by the protection relay. This will be the situation where the local and remote source voltage vectors are phase shifted with respect to each other due to pre-short circuit power flow. This can be resolved by choosing an option to utilize of a line current for polarisation of the reactance reach line. Polygonal impedance characteristics are greatly flexible in terms of short circuit impedance coverage for both line and ground short circuits. For this reason, most digital and numerical protection distance relays now give this shape of characteristic. An additional factor is that the extra cost implications of enforcing this characteristic utilizing discrete component electromechanical or early static protection relay technology do not happen.

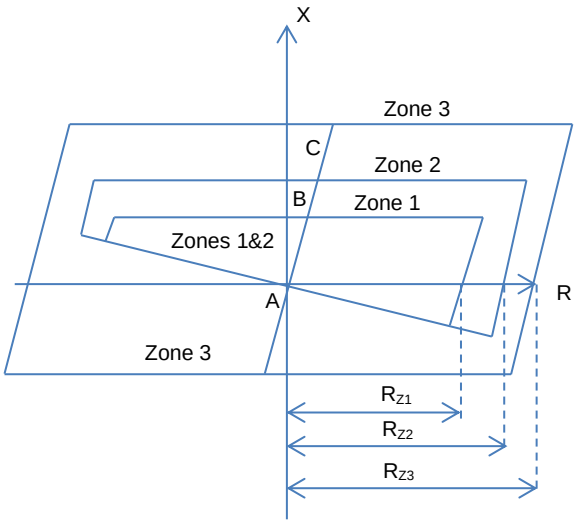


Figure 15. Quadrilateral characteristic

PROTECTION AGAINST POWER SWINGS – USE OF THE OHM CHARACTERISTIC

During serious power swing situations from which the power system is unlikely to retrieve, stability might only be recovered if the swinging sources are separated. Where such situations are discovered, power swing, or out-of-step, tripping relay protection can be used, to strategically divide a power system at a selected position. Ideally, the division should be made so that the plant capacity and loads on either part of the split are matched.

This disruption mode cannot generally be precisely described by typical distance protection. As previously noted, it is usually required to keep distance relay protection schemes from tripping during stable or unstable power swings, to avert cascade tripping. To start system division for a prospective unstable power swing, an out-of-step tripping arrangement using ohm impedance measuring devices can be used.

Ohm impedance characteristics are used along the forward and reverse resistance axes of the R/X graph and their tripping limits are set to be parallel to the protected transmission line impedance vector, as presented in Figure 16.

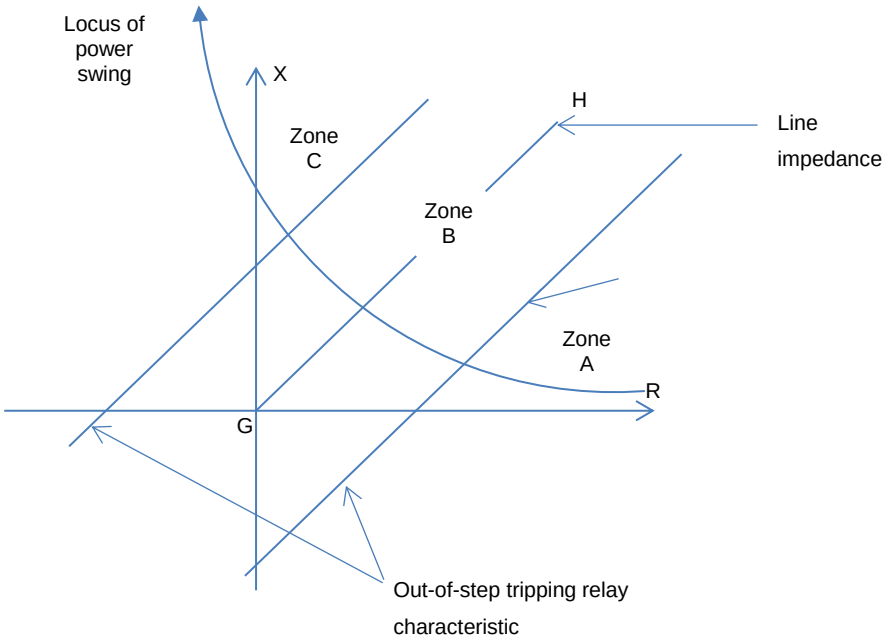


Figure 16. Usage of out-of-step tripping protection relay characteristic

The ohm impedance devices split the R/X impedance graph into three zones, A, B and C. As the impedance changes during a power swing, the point presenting the impedance shifts along the swing locus, entering the three zones in turn and making the ohm elements to trip in sequence. When the impedance gets into the third zone the trip sequence is finished and the circuit breaker trip coil can be energised at a favourable angle between power system sources for arc interruption with little risk of restriking.

Only an unstable power swing situation can make the impedance vector to shift through the three zones. Hence, other types of system disruptions, such as power system short circuit conditions, will not end in protection relay element trip.

OTHER CHARACTERISTICS

The performance time for the algorithm for typical distance relay protection using quadrilateral or similar characteristics may end in a long tripping time, perhaps up to 40 ms in some protection relay arrangements. To get over this, some numerical distance protection relays also use extra algorithms that can be carried out significantly quicker. These algorithms are based typically on sensing variations in current and voltage that are in surplus of what is anticipated.

This algorithm senses a short circuit by cross-comparing the measured quantities of current and voltage with the previously sampled quantities. If the variation between these samples surpasses a predefined quantity, it is presumed a short circuit has happened. In parallel, the distance to fault location is also calculated. Given the calculated distance to fault lies within the protection Zone reach of the protection relay, a trip command is issued. This algorithm can be carried out quicker than the typical distance algorithm, ending in quicker overall functioning times. Faulted line selection can be carried out by cross-comparing the signs of the variations in voltage and current. Protection relays that use these algorithms typically run both this and typical distance protection algorithms in parallel, as some short circuit types (e.g. high-resistance short circuits) may not fall within the short circuit detection criteria of the algorithm.

DISTANCE PROTECTION RELAY USAGE

Discriminating protection zones can be accomplished using distance protection relays given that fault distance is a simple function of impedance. While this is true for transmission lines, the impedances sensed by a distance protection relay also depend on the following points:

- the magnitudes of current and voltage (the protection relay may not see all the current that generates the short circuit voltage)
- the fault impedance loop being sensed
- the type of short circuit
- the short circuit resistance
- the symmetry of transmission line impedance
- the circuit arrangement (single, double or multi-terminal transmission line)

It is feasible to eliminate all of the above points for all practical operating situations. Nevertheless, significant success can be made with an adequate distance protection relay. This may incorporate protection relay devices or algorithms for starting, distance sensing and for scheme logic. Different distance protection relay formats exist and they depend on the tripping speed needed and cost conditions related to the protection relaying hardware, software or numerical protection relay processing capacity needed. The most typical formats are:

- a single sensing device for each line is given, that covers all line short circuits
- a more economical scheme is for ‘starter’ devices to check which line or lines have experienced a short circuit. The starter devices switch a single sensing device or algorithm to sense the most appropriate short circuit impedance loop. This is typically referred to as a switched distance protection relay
- a single set of impedance sensing devices for each impedance loop may have

their reach settings growingly raised from one zone reach setting to another. The gain happens after zone time delays that are started by functioning of starter devices. This type of protection relay is typically referred to as a reach stepped distance protection relay.

- each protection zone may be given with independent sets of impedance sensing devices for each impedance loop. This is known as a full distance protection arrangement, capable of providing the greatest performance in terms of speed and application flexibility

Moreover, relay protection against ground faults may need different characteristics and/or settings to those needed for line short circuits, ending in extra elements being needed. A total of 18 impedance-sensing devices or algorithms would be needed in a complete arrangement distance protection relay for three zone protection for all types of short circuits. With electromechanical or static arrangement, each of the sensing devices would have been a separate protection relay placed in its own enclosing, so that the distance protection relay comprised a panel-mounted assembly of the needed protection relays with suited inter-unit wiring.

Digital/numerical distance protection relays are likely to have all of the above functions incorporated in software. Starter elements may not be needed. The complete distance protection relay is placed in a single enclosure, making for great savings in space, wiring and enhanced dependability, through the enhanced availability that stems from the provision of uninterrupted self-supervision.

STARTERS FOR SWITCHED DISTANCE RELAY PROTECTION

Electromechanical and static distance protection relays do not typically use separate impedance-sensing device per phase. The cost and the final physical arrangement size made this arrangement impractical, except for the most comprehensive EHV transmission usages. To accomplish economy for other usages, only one sensing device was given, together with ‘starter’ elements that detected which lines were short circuited, to switch the adequate signals to the single measuring function. A distance protection relay using this method is known as a switched distance protection relay. A number of different modes of starters have been utilized, the most typical being based

on over-current, under-voltage or under-impedance sensing.

Numerical distance protection relays allow direct sensing of the lines involved in a short circuit. This is known as short circuit line selection, often abbreviated to line selection. Several methods are available for short circuit line selection, which then allows the adequate distance-sensing zone to operate. Without line selection, the relay protection risks having over or under-reach issues, or tripping three-line when single-pole short circuit clearance is needed. Several modes are available for short circuit phase selection, such as:

- Superimposed current comparisons, cross-comparing the step change of level between pre-short circuit load, and short circuit current. This allows very quick sensing of the faulted lines, within only several samples of the analogue current inputs

- change in voltage magnitude

- change in current magnitude

Numerical line selection is quicker than traditional starter methods utilized in electromechanical or static distance protection relays. It does not enforce a time penalty as the line selection and sensing zone algorithms operate in parallel. It is feasible to make a full-arrangement protection relay with these numerical methods. The line selection algorithm gives short circuited line selection, together with a segregated sensing algorithm for each line-earth and line to line short circuit loop (AN, BN, CN, AB, BC, CA), thus assuring complete-scheme operation.

Nevertheless, there may be situations where a numerical protection relay that mimics earlier switched distance protection methods is needed. The reasons may be economic (less software needed) - therefore cheaper than a protection relay that contains a complete-arrangement implementation) and/or technical. Some usages may need the numerical protection relay characteristics to match those of earlier generations already established in a transmission network, to help and enhance selectivity. Such protection relays are usable, often with refinements such as multi-sided polygonal impedance characteristics that help in averting tripping due to heavy

load situations. With electromechanical or static switched distance protection relays, a selection of available starters usually had to be made. The selection of starter was dependent on power system parameters such as maximum load transfer in relation to maximum reach needed and power system grounding schemes.

Where overcurrent starters are utilized, care has to be taken to assure that, with minimum generating plant in operation, the setting of the overcurrent starters is sufficiently sensitive to sense short circuits beyond the third zone. Moreover, these starters need a high drop-off to pick-up ratio, to assure that they will drop off under maximum load conditions after a second or third zone short circuit has been cleared by the first zone protection relay in the faulty section. Without this characteristic, indiscriminate operation may end for subsequent short circuits in the second or third protection zone. For acceptable tripping of the overcurrent starters in a switched distance protection scheme, the next conditions have to be met:

- the current setting of the overcurrent starters must be not less than 1.2 times the maximum full load current of the protected transmission line

- the power system minimum short circuit current for a short circuit at the Zone 3 reach of the distance protection relay must not be less than 1.5 times the setting of the overcurrent starters

On multiple-grounded power systems where the neutrals of all the power transformers are directly grounded, or in power systems where the short circuit current is less than the full load current of the protected transmission line, it is not feasible to use overcurrent starters. In these situations under-impedance starters are commonly used. The type of under-impedance starter utilized is typically dependent on the maximum anticipated load current and same minimum load impedance in relation to the needed protection relay setting to cover short circuits in Zone 3. This is shown in Figure 11 where Z_{D1}, Z_{D2}, and Z_{D3} are respectively the minimum load impedances allowed when lenticular, offset mho and impedance protection relays are utilized.

Distance Protection - Quiz

Updated: 11/3/2017

1. Distance protection is a form of unit protection.
   (A) True
   (B) False

2. Distance protection can be used to provide
   (A) Primary protection functions
   (B) Remote back-up functions
   (C) All of the above
   (D) None of the above

3. Distance protection uses _____ to locate and clear faults.
   (A) Voltage
   (B) Current
   (C) Impedance
   (D) Phase angle

4. Distance relay protects the line up to the _____ point.
   (A) Reference
   (B) Stop
   (C) Final
   (D) Reach

5. Distance protection relay operation is expressed in terms of _____.
   (A) Reach precision
   (B) Operating time
   (C) All of the above
   (D) None of the above

6. The power of a distance protection relay to precisely assess reach point fault is dependent on the _____ at the protection relay position under this condition.
   (A) Maximum voltage
   (B) Maximum current
   (C) Minimum impedance
   (D) Minimum voltage

7. The prime use of the protection relay polarising voltage is to ensure correct protection relay _____ response for close-up short circuit currents.
   (A) Forward
   (B) Reverse
   (C) All of the above
   (D) None of the above

8. Electromechanical/static protection relays typically have a reach setting of up to _____ of the protected transmission line impedance for instantaneous Zone 1 protection.
   (A) 90%
   (B) 70%
   (C) 80%
   (D) 60%

9. To assure complete coverage of the transmission line the reach protection setting of the Zone 2 protection need to be at least _____ of the protected transmission line impedance.
   (A) 100%
   (B) 120%
   (C) 110%
   (D) 105%

10. In electromechanical and static protection relays, Zone 2 protection is given by _____.
    (A) Different relays
    (B) Extending the protection reach of the Zone 1 relays after a time delay that is started by a fault detector
    (C) All of the above
    (D) None of the above

11. Zone 2 tripping has to be time-delayed to assure grading with the primary protection relaying used to adjacent transmission circuits that fall within the Zone 2 protection reach.
    (A) True
    (B) False

12. Protection Zone 3 reach should be adjusted to at least _____ the impedance given to the protection relay for a short circuit at the remote end of the second transmission line portion.
    (A) 0.8 times
    (B) 1.2 times
    (C) 2 times
    (D) 1.8 times

13. Zone 4 could be used to give back-up protection for the local bus.
    (A) True
    (B) False

14. The pain impedance characteristic does not take into account _____.
    (A) Phase angle between current and voltage
    (B) Angle between line resistance and reactance
    (C) All of the above
    (D) None of the above

15. Relays with pain impedance characteristic operate for all points inside the circle.
    (A) Outside
    (B) Inside
    (C) All of the above
    (D) None of the above

16. The impedance characteristic of a directional control device is a _____on the R/X graph.
    (A) Ellipse
    (B) Square
    (C) Circle
    (D) Straight line

17. Mho impedance device is inherently directional.
    (A) True
    (B) False

18. When the protection relay voltage drops to zero or near-zero, a protection relay using a _____ needs to be used.
    (A) Offset mho
    (B) Cross-polarised
    (C) All of the above
    (D) None of the above

19. Lenticular characteristic can allow greater degrees of transmission line loading than _____.
    (A) Offset mho
    (B) Plain impedance characteristics
    (C) All of the above
    (D) None of the above

20. Numerical protection relays typically use lenticular characteristic shaping.
    (A) True
    (B) False