Comparison of Quadrilateral and Mho Distance Characteristic

Solveig Ward

ABB Substation Automation and Protection Division
Allentown, PA

Presented to the

26TH Annual Western
Protective Relay Conference

October 26 – 28, 1999
Spokane, Washington

Comparison of Quadrilateral and Mho Distance Characteristic

Solveig Ward

Senior Application Engineer, Application Engineering and Consulting
ABB Substation Automation and Protection Division
Coral Springs, FL

Introduction

Many digital distance protections offer quadrilateral ground impedance characteristic, either as an optional complement to the mho characteristic or as the basic ground distance element. Quadrilateral characteristic was introduced in Europe in the 60s with the solid state distance relays as they often were applied for short lines in non-pilot systems without directional ground relays. Since then, it has become a general belief that the quadrilateral characteristic offer advantages to the mho characteristic, but very little data to support this exist.

It seems obvious that a quadrilateral ground distance characteristic would have better ground resistance coverage than a self-polarized mho characteristic, especially for short lines. However, is this also true for cross polarized mho characteristic using load encroachment blinders? Furthermore, the quadrilateral characteristic has a limited R/X setting ratio and precautions may have to be taken to avoid overreach due to load, while the conventional mho-characteristic is inherently load compensated. In addition, the reach of a quadrilateral impedance characteristic will always be limited by the minimum load impedance thus limiting the sensitivity for high resistive ground faults. A directional ground overcurrent relay, using zero sequence current only, does not have this limitation.

The few comparisons of quadrilateral and mho distance characteristics that have been made have generally been based on two relays of different design, one utilizing mho characteristic only and the other a quadrilateral characteristic, and possibly also containing mho elements. As the relays would utilize different measuring criteria, the results were not necessarily a reflection of the response of the mho and the quad characteristic only.

With the access to a mho distance relay with quadrilateral characteristic that can be selected ON or OFF, a direct comparison can be made. Apart from the impedance characteristic, all other supervision and logic operation criteria are the same.
When the quad is ON, the relay is using a "bullet" characteristic, i.e. a mho circle with a quad added to expand the characteristic in the resistive direction, see Fig. 1. The "tilt" of the reactive line illustrates the load compensation algorithm used and will either be downwards as shown in Fig. 1 (forward load flow) or upwards (reverse load flow). The importance of the load compensation feature is further described below.

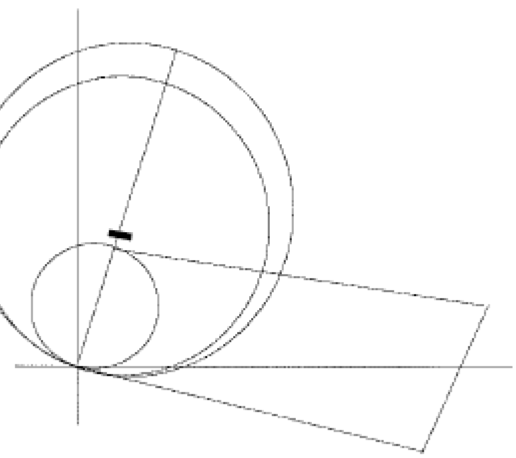

Fig. 1 Bullet impedance characteristic

This paper presents a comparison of the performance of this numerical distance relay with the basic mho characteristic and the same relay with the bullet characteristic. A number of different applications are discussed; radial and double-end-infeed conditions with load, non-pilot and pilot systems. The results are derived from theoretical studies and verified by EMTP bench tests and real time tests in a Model Power System.

Fault Resistance

While the fault resistance for three phase and phase-to-phase short circuits is given mainly by the arc resistance, two additional factors must be considered for ground faults; tower footing resistance and ground wires.

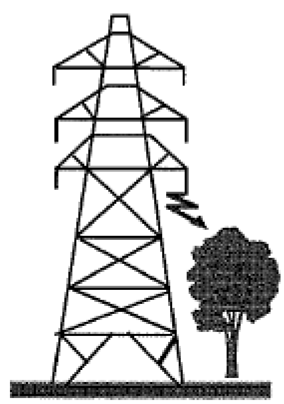

Fig. 2 Ground fault on a transmission line

The arc resistance varies with the fault current and also with time. A typical value of 1 or 2 ohms exists for around 0.5 seconds, with peaks of 25 to 50 ohms later. However, as the fault clearing time of a distance relay is relatively short, the fault resistance to be considered for phase faults; three phase and phase-phase, is comparatively small. Based on this fact, quadrilateral characteristic for phase faults is not discussed in this paper.

Tower footing resistance can vary from less than one ohm to more than 200 ohms. This resistance term must be added to the relay reach equations. When transmission lines have overhead ground wires, the effective resistance to ground is substantially reduced compared to the tower footing resistance of an individual tower.

For overhead lines without ground wires, the resistance to ground is equal to the grounding resistance of the affected tower. Most lines have values from 5 to 20 ohms but in rocky areas, the grounding resistance may be as high as 100 or even 200 ohms. Also critical are ground faults in the middle of wide spans caused by trees or forest fires that can have a very high ground resistance.

Impedance Characteristic

For a radial line without load the fault resistance R_f plots parallel to the resistive axis in an impedance RX diagram, see Fig. 3.

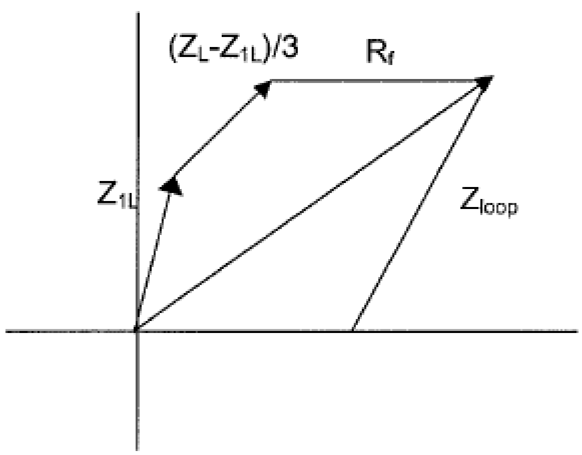

Fig. 3 Loop impedance

The loop impedance for a ground fault measured by the relay is

$$Z_{loop} = Z_{L1} + \frac{(Z_{L0} - Z_{L1})}{3} + R_f \qquad (1)$$

It is obvious that a ground quadrilateral characteristic seems to "fit" the fault impedance area in the RX diagram better than the ground mho characteristic, see Fig. 4. The quad

can provide a constant resistive reach along the line, while the resistive reach of the mho varies with the fault location.
The mho characteristic provides a circular impedance characteristic. As the impedance circle is a function of the reactive reach, i.e. the line impedance, the reach at the middle of the line might cover the desired fault resistance but at the end of the line, the resistive reach will be limited.

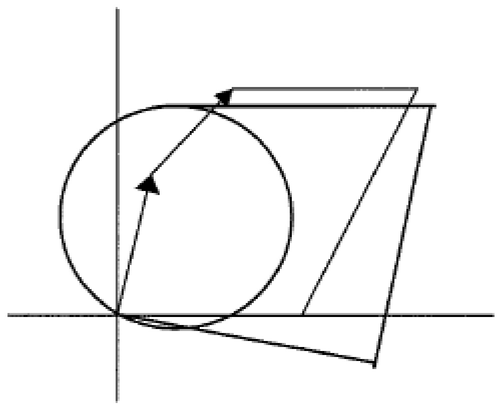

Fig. 4 Quad and mho characteristic

The presumed advantage of a quad compared to a mho relay is especially apparent for short lines where the R_f/X_L ratio, fault resistance/line impedance, is much larger, see Fig. 5.

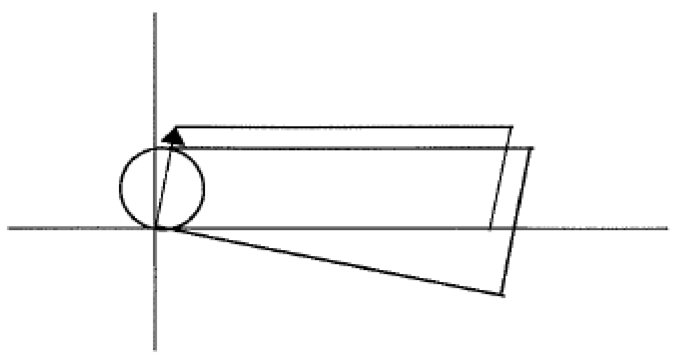

Fig. 5 Short line

The cross polarized mho ground elements substantially improve the situation as the circle will expand with the source impedance but the resistive coverage is still normally less than what a quadrilateral characteristic can achieve. See Fig. 6.

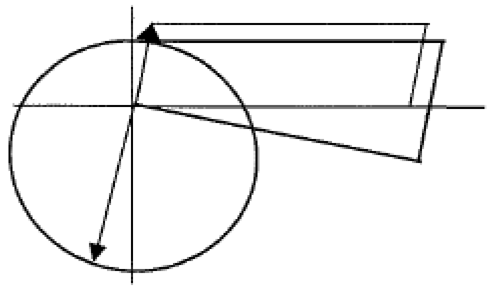

Fig. 6 Cross polarized mho

For long lines, the difference between mho and quad characteristic is less apparent, see Fig 7. It is important however, that the cross polarized ground mho relay is equipped with load restriction blinders in order to avoid load encroachment as the expansion of the mho circle is a function of the source impedance and can not otherwise be controlled. The traditional, cross polarized phase-phase unit will not respond to positive sequence current and voltage alone. It, therefore does not require a blinder.

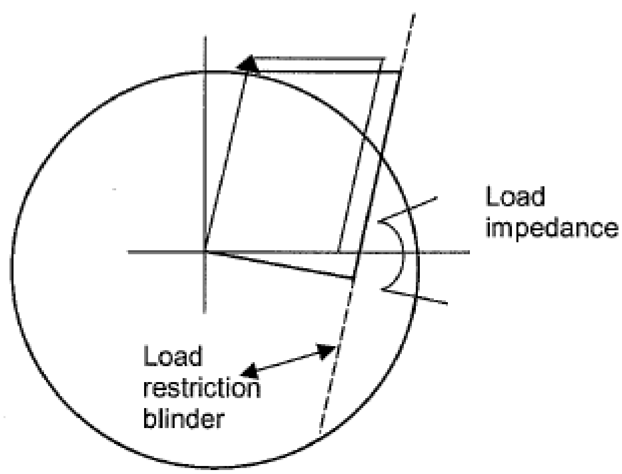

Fig. 7 Long lines

Ground Distance vs. Ground Overcurrent

The setting of a ground distance element is always limited by the minimum load impedance. This is true both for quadrilateral characteristic and mho characteristic with load restriction blinder.

Depending on the measuring algorithm used for the quad's resistive blinder, the setting will be restricted to 50 - 120 % of minimum load impedance. As the cross polarized mho does not have a defined setting in the resistive direction, prevention of load encroachment is made by introducing blinders into the scheme. The setting of this blinder is subject to similar restriction as for the quad's resistive blinder.

With a relay set to 90% of minimum load impedance, the maximum secondary fault resistance the ground distance element can detect will be

$$R_{f\max} = 90\% \cdot \left(\frac{V_{ph-ph}}{\sqrt{3} \cdot I_{load,\max}}\right) = 0.9 \cdot \frac{120}{\sqrt{3} \cdot 5} = 12.47\Omega \qquad (2)$$

assuming a maximum load current of 5A secondary.

A directional ground relay is not limited by the load impedance as it measures the zero sequence current. It can have a sensitivity of down to 0.5 A and $V_0 > 0.22$ V.

Using the system shown in the Model Power System test setup (see "Test Setup" below) the fault current can be calculated as

$$I_f = \frac{E}{\frac{2 \cdot Z_{S1} + Z_{S0}}{3} + Z_{L1}(1 + \frac{k_0}{3}) + R_f} \qquad (3)$$

where

$E = 70$ V	(driving EMF)
$Z_{S1} = 2.5$ ohms secondary	(positive sequence source impedance)
$Z_{S0} = 3.25$ ohms secondary	(zero sequence source impedance)
$Z_{L1} = 5.75$ ohms secondary	(positive sequence line impedance)
$k_0 = (Z_{L0}-Z_{L1})/Z_{L1} = 2$	(zero sequence compensation factor)
R_f	(fault resistance)

The fault resistance that can be detected on this particular line would vary from 137 ohms for a close in fault, down to 128 ohms for faults at the end of the line. Of course, this line has a fairly strong source and ground faults produce a substantial amount of fault current, why the limiting factor for the relay sensitivity mainly is the fault resistance itself. With a weaker source, i.e. higher source impedance, the ground fault relay sensitivity will be proportionally reduced. For a system with very high source impedance compared to the fault resistance, the source impedance will be the limiting factor for the relay sensitivity rather than the fault resistance.

The directional ground relay clearly has superior ground fault detection capability compared to any ground distance element. But, a disadvantage of a directional ground relay is that the sensitivity is source dependent as the fault current is not only a function of the fault resistance but also of the source impedance. This is of less importance for a pilot system where the ground relay is used in a directional comparison scheme but needs to be considered for non-pilot systems with inverse time delayed ground overcurrent relays. In a non-pilot system, the directional ground relay's current/time characteristic needs to be coordinated with the settings of the relays on the next line sections. In short line applications with weak sources this can be a difficult task.

One interesting observation is that the cross polarized mho characteristic will increase its resistive reach as the fault current decreases due to increasing source impedance, see Fig. 8. However, the minimum sensitivity of the ground distance element is the same as for the directional ground overcurrent relay, i.e. 0.5 A.

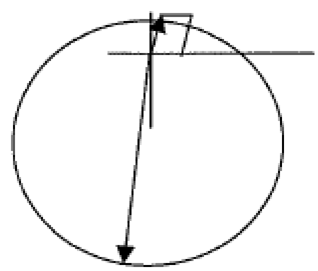

Fig. 8 Cross polarized mho characteristic for high SIR (source/line impedance ratio)

System Stability Considerations

One important aspect to consider regarding high resistance ground faults is the impact on system stability. Fig. 9 shows the influence of fault clearing time on system stability. A single phase to ground fault can be allowed for a much longer duration than a three phase fault as, even during the fault, the two unfaulted phases will still carry load current.

The actual system stability limit in MW is dependent on the system configuration and the values in Fig. 9 should be seen as guidance only. However, the difference in system stability consequences for a three phase fault compared to a single phase to ground fault is universally valid. As an example, the system stability limit allowing only 4 cycles of fault clearing time for a three phase fault can be compared to the >> 12 cycles fault clearing time required for a ground fault on the same system.

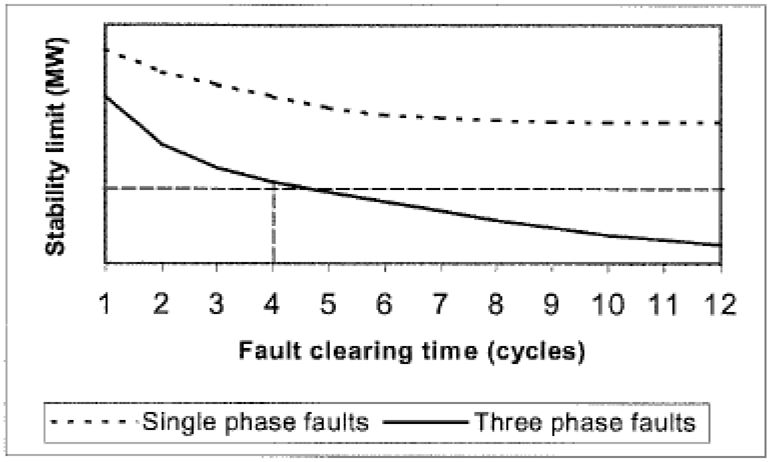

Fig. 9 Stability limit as a function of fault clearing time

Hence, from a system point of view, the well established practice to use directional ground relays (time delayed or in a directional comparison scheme) together with phase distance relays may provide a fully satisfactory protection system for most subtransmission and transmission line applications.

Ground Fault Impedance Characteristic

The characteristic shown for distance relays is normally the steady state, single end infeed characteristic. No influence of load or double end infeed is accounted for in this simple representation.

Mho ground distance elements are using phase comparators. The cross polarized mho is the most popular due to its system adaptability. The measurement for phase A ground distance element performs the computation of an operating quantity (4) and a polarizing quantity (5) as shown below, in a conventional manner. The measuring unit will provide an output when the operating quantity leads the polarizing quantity.

$$V_{AG} - \left[I_A + \frac{(Z_{0L} - Z_{1L})}{Z_{1L}} \cdot I_0 \right] \cdot Z_{set} \tag{4}$$

and

$$V_{CB} \tag{5}$$

where

V_{AG} is the faulted phase to ground voltage
I_A is the current in the faulted phase
Z_{0L} is the zero sequence line impedance
Z_{1L} is the positive sequence line impedance
I_0 is the zero sequence current
Z_{set} is the set impedance reach of the relay

V_{CB} is the phase to phase voltage between the unfaulted phases

This measurement algorithm forms a circle in the impedance plane, see Fig. 10.

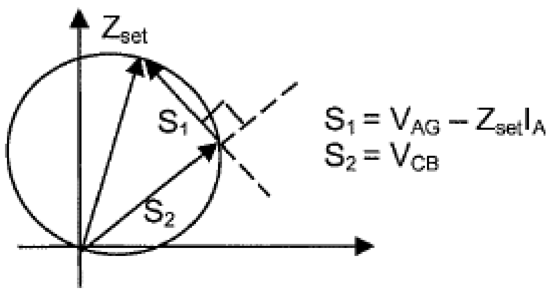

Fig. 10 Mho phase comparator principle

A quadrilateral characteristic plots as a polygon in the impedance plane. There is a vast variation of shapes and measuring principles employed. Some examples are shown in Fig. 11. Most quads are self polarized, i.e. the directional criterion that limits the characteristic in the reverse direction uses faulted phase voltage for its phase comparator.

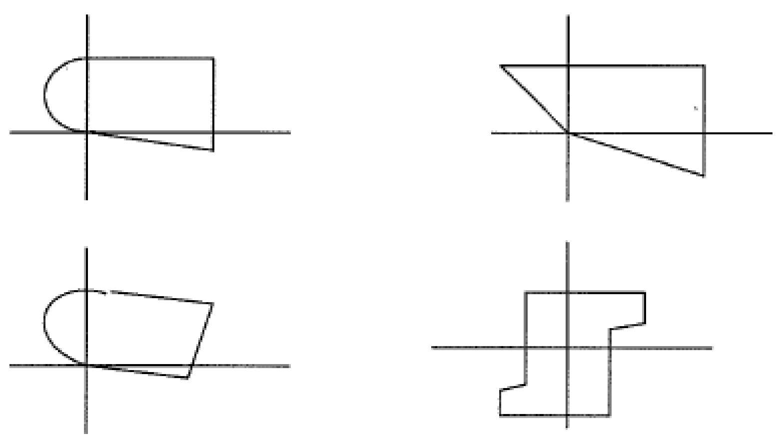

Fig. 11 Quadrilateral characteristics

Test Object

The tested relay uses a combination of a mho cross polarized circle and a Zone 1 quad "add-on", forming a bullet characteristic as shown in Fig 1.

The quad is a separate characteristic and operates in parallel with the mho circle in the relay. The comparisons have therefore been made on a relay with mho only and a relay with bullet characteristic, i.e. mho + quad.

The mho characteristic uses the well proven phase comparison principle, as shown in Fig. 10 above.

The quad is formed by four lines; the reactance line, the resistive blinder, the directional line and a left line closing the characteristic.

The reactance line is negative sequence polarized, providing load compensation. The line tilts upwards or downwards depending on the load direction, automatically compensating for the apparent increase or decrease of fault impedance presented to the relay. The load compensation greatly improves the performance during heavy load conditions. For export conditions, when the relay would tend to overreach, the line tilts downwards. Therefore, the Zone 1 reach does not need to be reduced to avoid overreach. For import conditions, when the relay would tend to underreach, the line tilts upwards.

The resistive line does not use zero sequence current, only phase current, to avoid load encroachment of healthy phases during ground faults. It is therefore difficult to correctly illustrate the characteristic in a positive sequence impedance plane. However, principally, the steady state characteristic can be shown as a quadrilateral area in the impedance diagram as in Fig. 12.
The directional line is self polarized and forms a 90 degree angle with the set line angle.

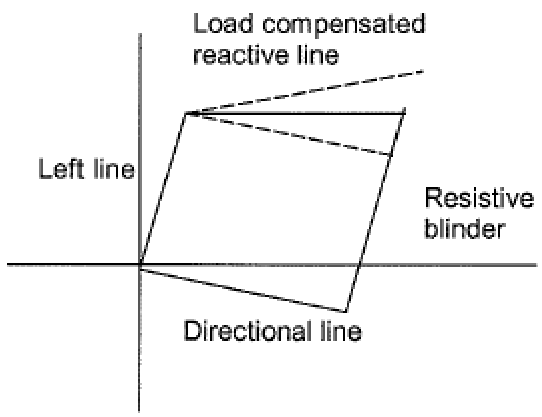

Fig. 12 Quadrilateral characteristic

Test Setup

The non-pilot radial systems were tested with a bench test set using EMTP generated data. The double end infeed pilot systems were tested in a Model Power System (MPS) providing real time simulation. The system parameters in the MPS setup were also used for the theoretical studies and the bench testing. The system set up is shown in Fig. 13.

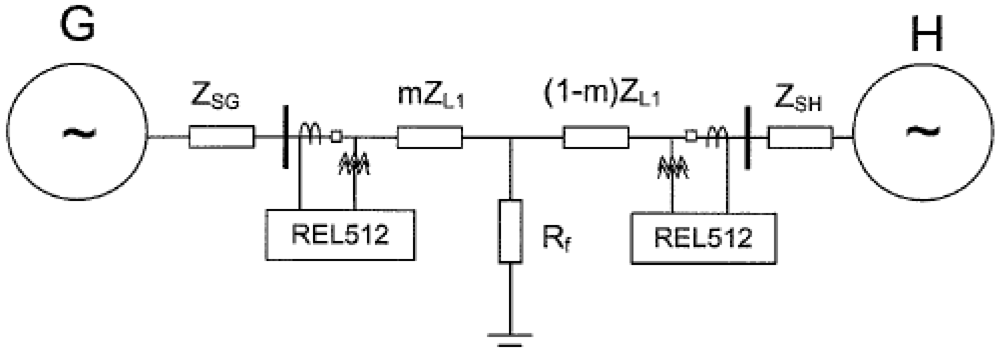

Fig. 13 Model Power System Test Setup

The fault location, m, was varied between 0 and 80% of the line length. The relays were set to 90% of the total line impedance. The fault resistance was increased until the relays stopped operating, thus giving the maximum fault resistance detection capability possible for the relay characteristic.
Tests were made for both load and no load conditions.

The relay at G was used for measurement of test result and the only task for the relay at H was to provide a permissive carrier signal for the pilot system testing.

The following system parameters were used:

Z_{SG1} = 2.5 ohms	(positive sequence source impedance for G)
Z_{SG0} = 3.25 ohms	(zero sequence source impedance for G)
Z_{L1} = 5.75 ohms	(positive sequence line impedance)
Z_{L0} = 17.375 ohms	(zero sequence line impedance)
Z_{SH1} = 5.0 ohms	(positive sequence source impedance for H)
Z_{SH0} = 6.5 ohms	(zero sequence source impedance for H)

The MPS setup represents a typical, medium long line, e.g. 20 miles. The source impedance values are also typical for most transmission system. The tests with load had a power transfer from G to H of 3.5 A. Note, all values are on a secondary basis, 120V, 5A.

Radial Systems

Distance relays are rarely applied on radial systems and the only reason they are included in this paper is for the simplicity of describing the distance relay operating characteristics for this application. On a radial line, the relay will respond according to the theoretical steady state characteristics.

A distance protection on a radial line is applied in a stepped distance scheme. This means that instantaneous tripping is made from an underreaching Zone 1 and the remaining 10 to 20% of the line will be tripped by an overreaching time delayed Zone 2, see Fig. 14.

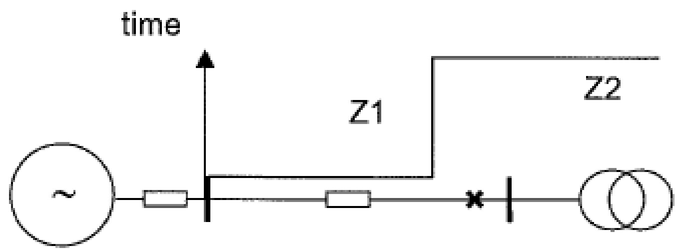

Fig. 14 Stepped distance scheme

For radial lines, the advantage of the quad is obvious. This is especially true for short lines with a strong source behind the relay, i.e. with small source impedance. For these applications, the cross polarized mho circle expansion in the resistive direction is small, resulting in poor resistive coverage. The quad does not have this disadvantage, as the resistive reach is source independent. This is illustrated in Fig. 15. Bench testing confirms the theoretical analysis.

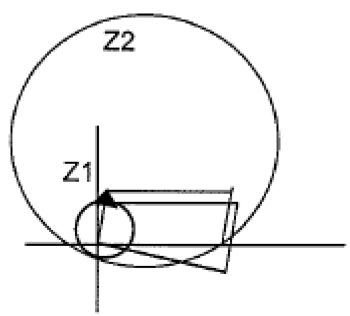

Fig. 15 Radial line with strong source

Pilot systems are rarely used for radial lines. A blocking scheme or a POTT with weakfeed logic could be applied, however, and then the discussion below for "Pilot Systems" would be valid also for radial lines.

The Effect of Double End Infeed and Load on Fault Impedance

Overhead ground wires substantially reduce the line zero sequence impedance and the tower footing resistance component. To the relay, however, the effect is not a pure resistive component. For fault calculations, the ground wire is assumed to be parallel with the earth. In practice, its impedance is parallel with the earth through the tower footing resistance at each tower. This effect tends to force more of the return current in the ground wire, decreasing the earth return current.

The infeed from the remote line end will influence the apparent impedance seen by the relay. The effect varies with the fault location and the source impedances. The influence will be most pronounced for the local relay for a phase to ground fault at the far end of the line.

The effect is shown in Fig. 16. The apparent impedance Z_A is the sum of the line impedance Z_L, the tower footing impedance Z_{TF} and the zero sequence self impedance Z_S. While the ground wires significantly have reduced the tower footing impedance of the individual tower, the resulting angle will cause problems with all types of underreaching ground distance schemes.

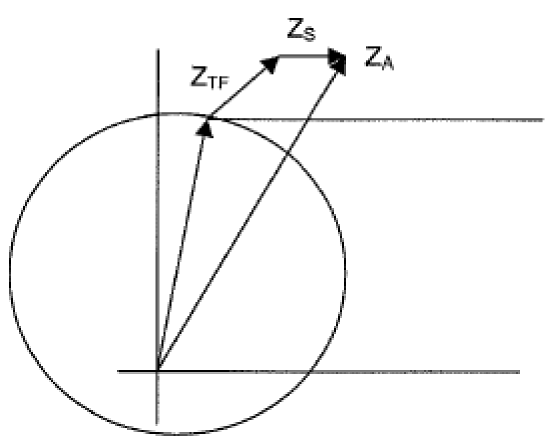

Fig. 16 Effect of ground wires on tower footing and arc resistances

The above illustration does not take into account load flow. With load, the apparent fault impedance presented to the relay is even further affected.

Consider the double end infeed system illustrated in Fig 17. The distance relay has access only to the current in its own line end and can not measure the actual fault current I_f flowing through the fault resistance. We can see that the fault current I_f has two components, originating from the two sources, G and H, at the two line ends.

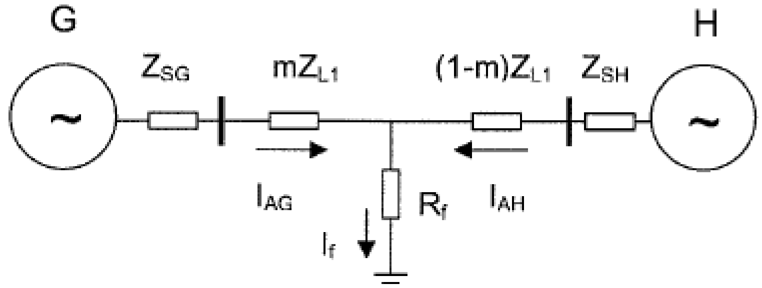

Fig. 17 Double end infeed system

The fault equation for a phase A to ground fault is:

$$V_A = mZ_{1L}(I_A + k_0 \cdot I_0) + R_f \cdot I_f \qquad (6)$$

where

V_A is the faulted phase to ground voltage
mZ_{1L} is the positive sequence line impedance up to the fault location
I_A is the current in the faulted phase
k_0 is the zero sequence compensations factor:

$$k_0 = \frac{Z_{0L} - Z_{1L}}{Z_{1L}}$$

Z_{0L} is the zero sequence line impedance
R_f is the fault resistance
I_f is the fault current through the fault resistance R_f

For power to have been flowing before the fault, the two sources at the two line ends, G and H, must be out of phase. Typical values are 10 to 30 degrees. When the fault occurs, the machines hold this phase relationship for some time. The summation fault current I_f therefore has a phase position which does not match the phase of the current flowing from either terminal, G or H. It is somewhere in between, depending on relative contributions, which in turn depend on the fault location and on network distribution factors.

If the fault resistance is zero, $R_f = 0$, the fault current I_f does not produce any voltage drop and has no effect on the impedance calculation from either end. But with a large fault resistance, that may be the case for a ground fault, the fault current I_f will give a voltage drop that is not in phase with either mesh current. Even if R_f were a pure resistance, it appears as a complex impedance to the relay measuring the loop impedance from either end. From the power sending end (forward load flow), the fault path leads the local current and the apparent capacitive reactance subtracts from the inductive line impedance. The relay will tend to overreach. At the receiving end, the apparent reactance is inductive and adds to the line impedance. The relay will tend to underreach. This effect of load flow is illustrated in Fig. 18. The dashed line represents the locus of the fault impedance with increasing fault impedance. With R_f = infinite, i.e. no fault, the apparent impedance enters the load area on the resistive axis in the impedance plane. Depending on the direction of the load flow, it will either be along the positive R-axis (forward load) or the negative R-axis (reverse load).

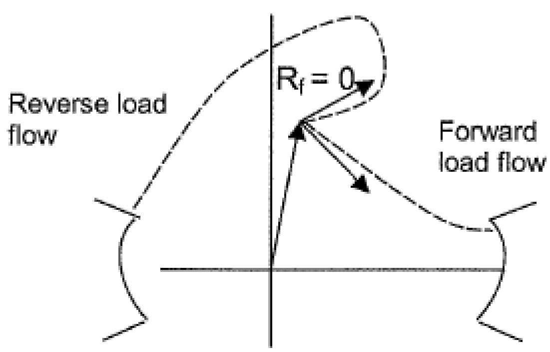

Fig. 18 Effect of load flow on fault resistance

The mho characteristic has an inherent adaptation to load flow. The mho units will "tilt" in a beneficial manner as illustrated in Fig. 19. The dashed circle shows the steady state characteristic and the solid circle represents the actual, load compensated mho characteristic.

For forward load flow a reactance characteristic would tend to overreach for an external fault. The mho circle is expanded and shifted to the left in the impedance plane so that the resulting apparent fault impedance is outside the operating characteristic.

For reverse load flow a reactance characteristic would tend to underreach for an internal fault. The mho circle is expanded and shifted to the right in the impedance plane so that the resulting apparent fault impedance falls within the operating characteristic.

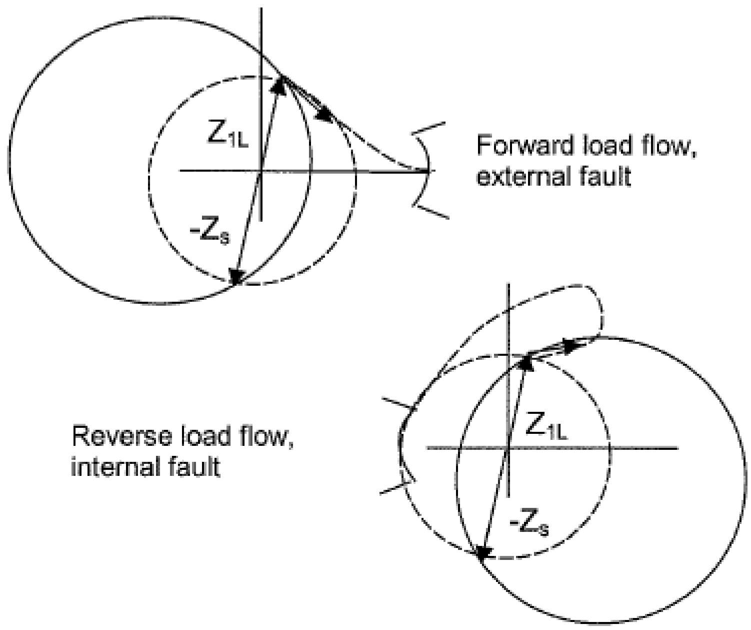

Fig. 19 Mho load compensation characteristic

A quadrilateral ground characteristic for an underreaching zone needs to either suffer a reach reduction to avoid overreach, or use a load compensated algorithm for the reactance line, see Fig 20.

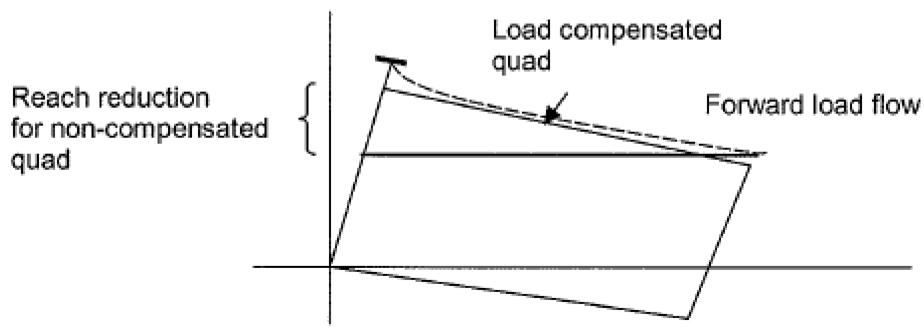

Fig. 20 Quadrilateral characteristic during forward load flow

The reach reduction required for a non compensated reactance line can be substantial, 10 – 30 %, depending on the system parameters and maximum forward load flow. A non compensated reactance line will underreach for reverse load and, of course, any reach reduction introduced to compensate for possible forward load will further deteriorate the performance of an underreaching Zone 1. "Smart" compensation will correctly compensate for reverse load flow as well. This is illustrated in Fig. 21.

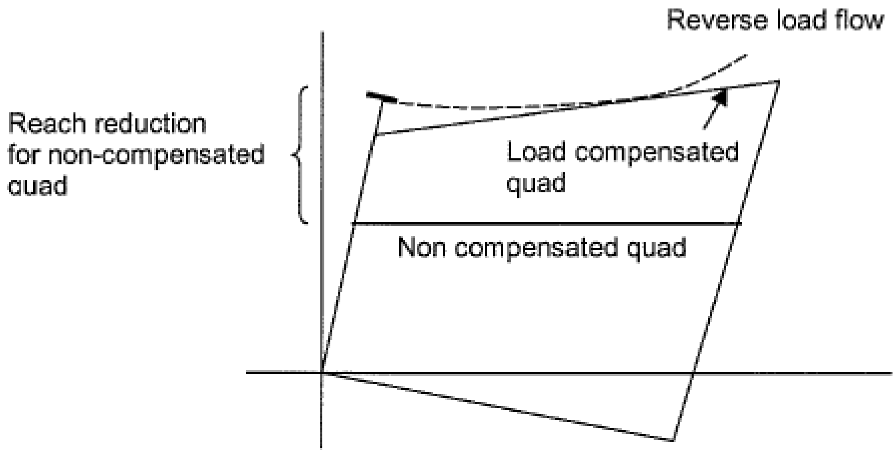

Fig. 21 Quadrilateral characteristic during reverse load flow

The apparent increase in fault impedance due to double end infeed will affect both a mho characteristic and a quad, load compensated or not. Fault locator algorithms have been developed that successfully compensate for the contribution to the fault current from the remote end. However, these require memorizing pre-fault currents and the presently available methods to use this data for fault computation are too slow to provide high speed distance protection.

The practical solution for lines with substantial remote infeed will be to use an overreaching pilot scheme and/or directional ground overcurrent protection as a complement to the distance protection.

Non Pilot Systems (Stepped Distance)

A non pilot system is totally dependent on Zone 1 operation for instantaneous tripping. Ground directional overcurrent relays have to be time delayed as they do not have a defined reach.

A non pilot distance protection scheme has to deal with double end infeed effect on fault resistance by either sequential tripping or by accepting Zone 2 operating time.

Sequential tripping takes place when the relay closest to the fault trips instantaneously as the remote infeed effect on the fault resistance is less. The remote relay might then be able to detect the fault when the system is reduced to a radial line, and trip sequentially.

Zone 2 , time delayed operation, might also be acceptable as a ground fault can be allowed longer fault clearing time from a system stability point of view.

Test Results for Double End Infeed Conditions in Stepped Distance Schemes

As mentioned above, tests for double end infeed conditions were made in a Model Power System (MPS), see Fig 13. For simplicity, high resistive ground faults were applied only at three locations from G; 0%, 50% and 80%. Zone 1 reach was set to 90% of the line impedance and the fault resistance setting for the quad was 12Ω/loop. The load current was 3.5 A.

In the graphs shown below in Fig. 22 (no load) and Fig. 23 (3.5 A load), intermediate points have been entered based on theoretical studies. Theoretical analysis and actual MPS tests agree.

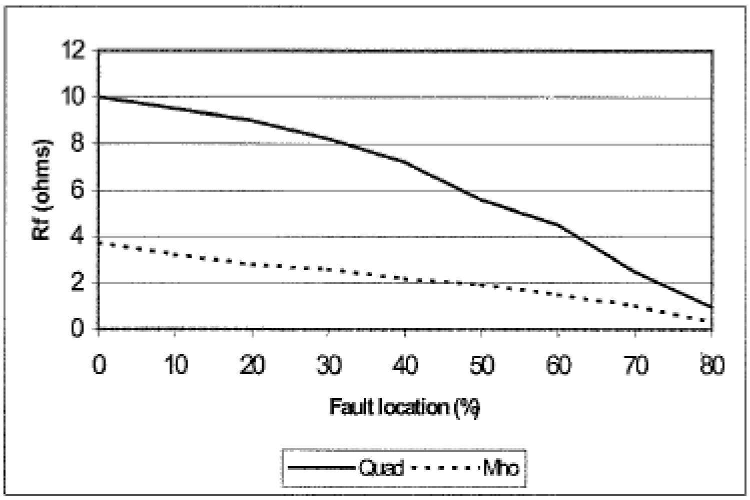

Fig. 22 MPS testing of stepped distance scheme without load

For the system set up in the MPS, the results show clearly that that the quadrilateral characteristic is superior to a mho ground distance relay for stepped distance protection. The reason is obvious. As pointed out earlier, the scheme is totally dependent on the underreaching Zone 1 and even the cross polarized mho characteristic can not match the performance of a quad with a setting extended to the permissible maximum. That the theoretical reach of 12 Ω is not achieved is, of course, due to the apparent increase of the fault resistance by the infeed from the remote end.

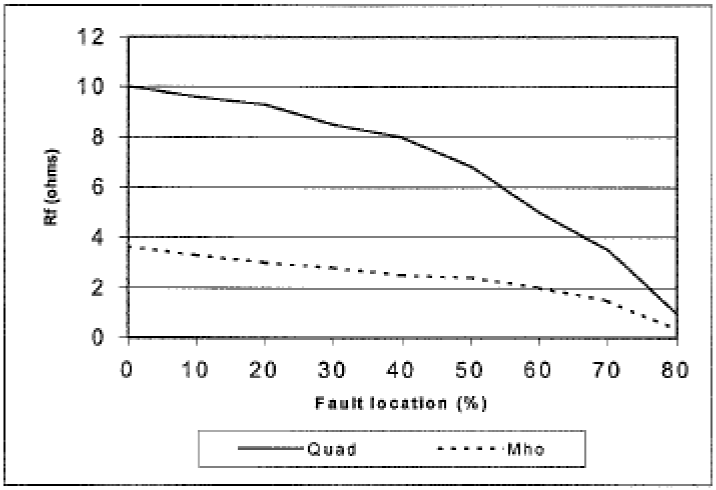

Fig. 23 MPS testing of stepped distance scheme with load

One interesting observation is that both characteristics slightly improve during forward load conditions. This is the result of the inherent load compensation capability in the mho cross polarized measurement and the reactance load compensation algorithm used for the tested quadrilateral characteristic.

Pilot Systems

For an overreaching pilot scheme, such as blocking or POTT, the operating characteristic is of less importance than for a non-pilot scheme. With an independent pilot zone, the reach of the mho characteristic can be extended to 200-300% of the line impedance. For short line or three terminal applications, pilot reach settings of 1000% or more are not unheard of.

For a mho characteristic, the increase in reactive reach will directly result in increased resistive coverage as well. A large overreach of the protected line impedance does not introduce any problems as long as the relay includes an independent Zone 2. The Zone 2 reach needs to be coordinated with the protections on the next line section(s), but the reach of the pilot zone does not. On parallel line applications, transient block logic efficiently eliminates possible problems due to sequential clearing when the pilot zone detects faults on the parallel line. Of course, the load restriction blinders are essential to avoid load encroachment during ground faults. In fact, as shown in Fig. 24, the pilot mho characteristic, with blinders, approach a quad characteristic when the zone reach is much larger than the line impedance.

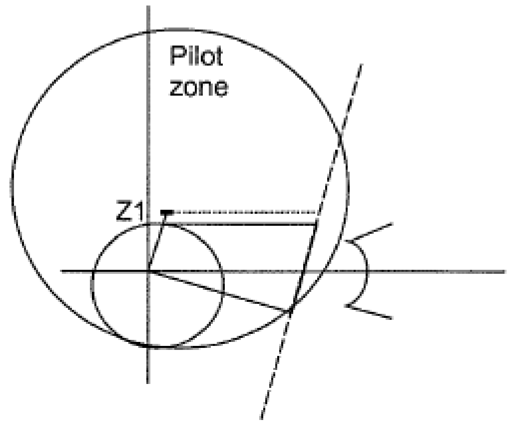

Fig. 24 Mho characteristic in a pilot system

From Fig. 24, it is also apparent that the pilot system successfully deals with the double end infeed negative influence on the fault resistance. Of course, this is also valid for a pilot quad zone but it is of utmost importance that the pilot zone is independent from a reach limited Zone 2.

Test Results for Double End Infeed Conditions in Pilot Schemes

As mentioned above, tests for double end infeed conditions were made in a Model Power System (MPS), see Fig. 13. For simplicity, high resistive ground faults were applied only at three locations from G; 0%, 50% and 80%. In the graphs shown below in Fig. 25, intermediate points have been entered based on theoretical analysis. Theory and actual MPS tests agree. The pilot zone reach was set to 300% of the line impedance.

No comparison was made for a quad and a mho distance relay. Based on the discussions above, the impedance shape is of less, or no, importance for an overreaching pilot system.

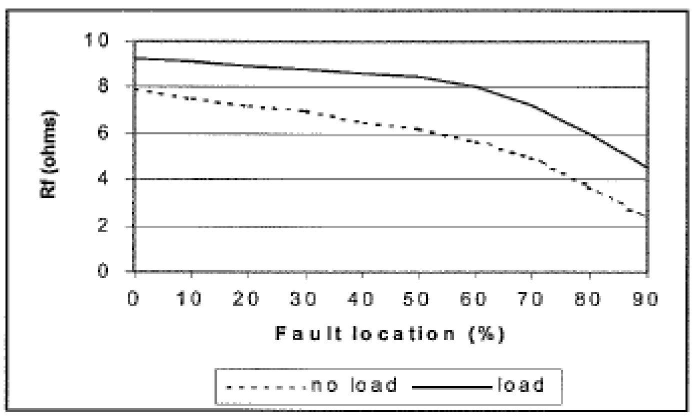

Fig. 25 Fault resistance detection capability for double end infeed

Again, it is interesting to see how forward load improves the ground distance relay ground resistance coverage. This is a result of the decrease of the apparent impedance caused by the contribution to the zero sequence current component from the load currents in the two unfaulted phases.

From the results, it is obvious that the fault resistance detection capability along the entire protected line is far superior for a pilot system than for a stepped distance scheme. There is still, however, a resistive reach reduction close to the line end (on the right side in the figure) due to the heavily increased apparent fault impedance caused by the infeed from the remote source. As mentioned before, for high resistive ground fault detection, the ground directional relay surpasses any distance relay characteristic. Consequently, a distance pilot scheme for lines subjected to high resistive ground faults, heavy load flow and double end infeed benefits greatly from a built-in directional ground function.

Mutual Coupling on Parallel Lines

It is a well known fact that zero sequence mutual coupling causes underreach and overreach problems for ground distance elements. The tendency for overreach is normally compensated for by reducing the Zone 1 reach. This reduction applies to both a mho distance relay and a quad distance relay why the effect of mutual coupling has not been taken into account for the comparison made in this paper. It is strongly suggested that distance pilot systems are used on parallel lines with mutual coupling as an underreaching Zone 1 can not be relied upon to cover the entire protected line during all fault conditions. As mentioned above, the choice between mho and quad characteristic is then of little importance.

Summary

With modern microprocessor relays, any operating characteristic can be realized. However, many of them use the well proven mho characteristic due to its popularity. This popularity is well earned.

The mho ground distance element provides the following features:

- excellent field experience
- familiarity to all relay engineers
- easy to test
- adequate fault resistance detection capability for a majority of applications
- inherent load compensation capability
- fault resistance detection capability for pilot systems is as good as for a quadrilateral characteristic

Quadrilateral ground distance characteristic is beneficial for some applications, namely:

- stepped distance, non-pilot systems
- short lines with strong sources when directional ground relays are not used as a complement to the distance protection

Ground directional overcurrent provides

- best sensitivity

References

1. C. F. Wagner and R. D. Evans, *Symmetrical Components*, Robert E. Krieger Publishing Company, Inc., Malabar, FL, 1982

2. J. Lewis Blackburn, *Protective Relaying*, Marcel Dekker, Inc., NY, 1987

3. W. A. Elmore et al, *Protective Relaying Theory and Applications*, Marcel Dekker, Inc., NY, 1994

4. W. A. Elmore et al, *Evolution of Distance Relaying Principles*, Georgia Tech Protective Relaying Conference, Atlanta, GA, May 1995

5. Damir Novosel et al, *New Methods for Using Relay Data to Locate Faults*, Texas A&M Protective Relaying Conference, College Station, TX, April 1996

Biography

Solveig Ward received her M.S.E.E. from the Royal Institute of Technology, Stockholm, Sweden in 1977 and was employed by ABB Relays in Sweden from 1977 to 1992. During that time she held many positions in Marketing, Application and Product Management. Since 1992, she is employed as Senior Application Engineer in the Product Management and Consulting Department at ABB, presently in Allentown, PA. Solveig has extensive experience in development and application of numerical distance protections and is currently responsible for the new line of numerical current differential and phase comparison line protections.
She is a member of IEEE and holds one patent, "High Speed Single Pole Trip Logic".