

TRANSMISSION LINE PROTECTIVE SYSTEMS LOADABILITY

**A report to the
Power System Relay Committee of
the IEEE Power Engineering Society**

prepared by working group D6

Abstract

This paper is about the effects of protective relaying on the loadability of transmission lines. The calculation of relaying load limits for use in comparing to transmission line load limits or other limits is discussed. The identification of problems associated with the application of relay protection that result in the interference of line loading capabilities is covered. This is followed by the discussion of methods available that are aimed at increasing the loadability of relay schemes while also maintaining required levels of relay coverage and security.

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1. Introduction

As transmission lines are loaded to higher and higher levels, and as the concept of open transmission access becomes a reality, the subject of load-carrying capabilities of transmission lines is becoming increasingly important. Short term ratings of lines are being applied for system operations, and conflicts with load limitations and the protection system settings are becoming more prevalent.

Generally, the characteristics of the line itself should determine the limits of line loading. The level to which the protection system permits a transmission line to be loaded is based on transmission line protection design and setting philosophies, system characteristics, and protective equipment thermal ratings. A line relay load limit is established for the purpose of comparing with the line load limit to determine if steps must be taken to prevent undesirable relay operation.

This paper discusses the various factors to consider concerning relays in the determination of transmission line loadability; considerations for protection design and relay setting philosophies to prevent limitations on line loadability; and utility practices for settings, equipment ratings, and methods to mitigate related problems.

2. Fundamental Concepts of Loadability

2.1 Definition of Relay Load Limit

For the purposes of this document, the line relay load limit will be defined to be the loading permitted by the relay including a security margin. The direction of power flow may or may not be a factor depending on the relay

2.2 Calculation of Load Limits

Protective relay load limits are often conservative, with some room provided for equipment errors and some fluctuation in the loading. The amount of these margins is dependent upon the amount of risk of load induced protection trips the user is willing to accept. Therefore when calculating load limits, it is wise to recognize the role that margins play, and to clearly state whether or not the calculated limits include any margins. The following discussion on calculation will include consideration of margins.

2.2.1 Overcurrent Relays

These relays respond to a specific value of current which can be converted to a specific load by multiplying by the operating voltage. However, since current magnitude is sometimes available to operators, it is better to state the load limit in terms of current. The current load limit is the magnitude of current at which the relay is expected to start timing towards its trip condition. When considering this limit, it is important to be aware of two factors:

a) The overcurrent relays, line current monitors, and the interposing transducers exhibit finite accuracy. Therefore it is possible that the relay may operate at a current lower than the set current or the monitored current.

b) The load current may sometimes remain considerably above the steady state level for an amount of time in excess of the relay operating time. The usual cause of sustained high load currents is cold load pickup, when load currents may remain at 50% to 100% higher than the steady state value.

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Overcurrent relays are typically applied on subtransmission lines that are more susceptible to cold load pickup conditions than transmission lines.

When the above two factors are considered it is clear that the load current limit should include a safety margin. A margin of 10 to 20 percent is typical if cold load pickup is not a factor. A higher margin is more appropriate if cold load pickup is a possibility. The trip point load limit (without margin) of an overcurrent relay set to trip at a current I (in amperes), can be expressed in terms of "Trip Point Amps" or as "Trip Point MVA" at a given line to line voltage V_{LL} (in volts). These values can be calculated by:

$$S_{max} = \sqrt{3} * V_{LL} * I \text{ where all values are physical units} \quad (1)$$

Appendix A gives an example of a loadability calculation for a transmission line overcurrent relay.

2.2.2 Distance Relays

These relays respond to an impedance of varying magnitude which depends on the power factor of the load impedance. Their load limit is normally quoted in MVA, at nominal operating voltage at some specified power factor. This point is chosen to be conservative enough to exceed expectations of actual line load levels and power factors. The distance relay definite time delays are usually much faster than those of overcurrent relays; so margins have to allow for larger transient conditions (with shorter duration) than is the case with overcurrent relays. On the positive side, since these relays are usually applied on transmission lines which are not exposed to the cold load pickup phenomenon, such load pickup is not usually a concern.

The most commonly encountered distance characteristic is the mho. Other distance relay characteristics will exhibit different responses to loading and may be more or less appropriate for use in situations where loading is a problem. (See Appendix B)

Figure 1 shows the apparent impedance of the load with respect to a distance relay with a forward reaching mho characteristic.

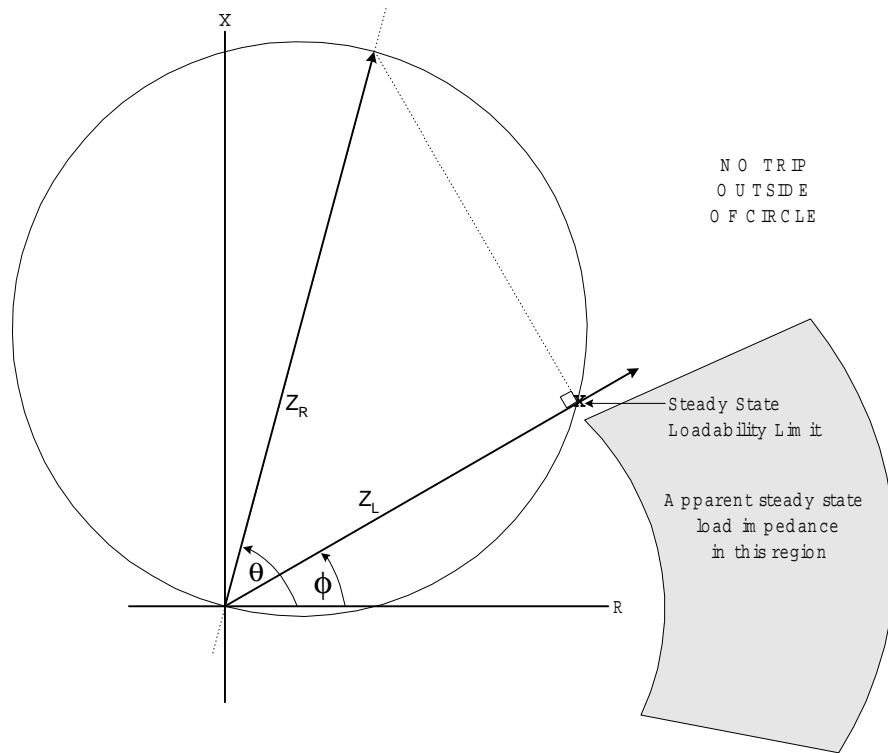


Figure 1: Loadability calculation for mho characteristic

When calculating the margin, it is important to consider the effect of the full range of load power factor. (as shown in the gray area) The impedance reach at the steady state loadability limit Z_L (without margin) of a mho characteristic of known reach Z_R , with a maximum torque angle of θ and at a power factor of $\cos(\phi)$ is determined by the geometry of the mho circle as

$$Z_L = Z_R * \cos(\theta - \phi) \quad \text{As shown in Figure 1} \quad (2)$$

To calculate the power S_{max} at a given voltage V_{LL} at the positive sequence impedance Z (ohms) at the loadability limit, the applicable formula is

$$S_{max} = V_{LL}^2 / Z \quad (3)$$

When using the above calculated loadability limits for planning or operating purposes, it is important that the user be advised whether the limits include any margins.

Appendix A gives examples of a loadability calculation for two transmission line mho relays. The above calculations can be adopted for forward or reverse reaching mho relays as depicted in figure 4.

2.2.3 Current Differential Relays

Current differential relays respond to the differential current formed in the relays using the measurements from all the line terminals transmitted over a fast communications channel. The differential signal formed internally by the relay to reflect an internal fault current is compared to a restraint signal. The comparison is made using a multi-slope percentage characteristic.

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Current differential relays are almost completely immune to increased load on a protected line. As the load current increases, the spurious differential current caused by finite CT accuracy will increase, but at the same time, the restraining current will increase as well. The percentage characteristic ensures relay stability for any amount of overload. This scheme is affected by tapped loads on the line. The presence of tapped loads may prevent this scheme from being utilized on the given line.

Generally, as a rule, the current differential relays are backed-up by overcurrent and/or distance relays (primarily to back-up against loss of communication channel). Consequently, the lines protected by current differential relays may face similar loadability problems as those protected by overcurrent relays, stepped distance relays or distance pilot schemes because of the presence of these backup relays.

2.2.4 Phase Comparison Relays

These relays respond to phase relation between the currents at all the terminals of a protected line. The relation between the phase angles of the currents is typically checked by monitoring the time alignment between the rectified currents. In order to reduce the required bandwidth of the communication channel, a single operating signal is often formed out of three phase currents and the correlation is checked once a cycle (single-comparison relay) or twice a cycle (dual-comparison relay).

Phase comparison relays have a current level detector which starts the comparison of the local and received pulses. Due to the potential for misoperation caused by noisy communication, the comparison is normally not activated. Increasing the starter level detector for increased load will decrease low magnitude fault detection. As the load current increases, the relationship of the phase angles of the currents at the line terminals remains consistent thereby preventing false tripping. This scheme is affected by tapped loads on the line. The presence of tapped loads may prevent this scheme from being utilized on the given line.

Like the current differential relays, the phase comparison relays are often backed-up by overcurrent and/or distance relays (to cover loss of communication channel). As a consequence, the lines protected by phase comparison relays may face certain loadability problems because of the presence of these backup relays.

3. Factors Affecting Line Loadability

3.1 Protective Equipment

When determining the loadability of a transmission line, the limitations due to the protective equipment must be considered.

3.1.1 Relays

Published relay characteristics are based on the operation of relays within specified limits of environmental conditions and electrical inputs. The accuracy and sensitivity of relays change (generally decrease) when the relays are operated outside of the specified limits.

3.1.1.1 Relay Ratings

The ANSI/IEEE C37.90 standard [1] specifies standard service conditions, standard ratings, performance requirements, and requirements for testing of relays and relay systems used to protect and control power apparatus. With regard to loadability, the following pertinent ratings should be considered: the standard current and voltage ratings, maximum design current and voltage at which the relay is designed to be

energized continuously, and the total temperature of relay coils which is the sum of the temperature rise of coils and the ambient temperature.

The effect of higher currents, voltages, and ambient temperature is to increase the total temperature inside the relay. Higher relay temperatures reduce relay insulation life. Also, the sensitivity and accuracy of the relay most likely will be decreased. Therefore, from a thermal point of view, if the sensitivity, accuracy, and service life of the relay is to be preserved, the continuous load current should not exceed the maximum design current at which the relay can be energized continuously.

If the average ambient temperature in a given installation exceeds the rated ambient temperature, then the continuous currents and voltages applied to the relay need to be derated to avoid the thermal consequences mentioned above.

3.1.1.2 Overcurrent Relays

The aforementioned standard [1] specifies the standard current ratings, but does not specify the highest current at which the relay can be energized continuously. Through the years, relays have been designed to meet or exceed the standard current ratings. Consequently, the margin by which the maximum continuous current exceeds the standard current rating varies from relay to relay and manufacturer to manufacturer. Typical values of maximum continuous currents for overcurrent relays are usually 2-3 times nominal tap current. If overcurrent relays are connected to trip, they usually cannot be subjected to steady state currents greater than their pickup tap setting (because the relay will trip the circuit shortly after the current exceeds the pickup tap setting). Thus their maximum continuous rating is not usually a factor in limiting line loadability, unless their tripping function has been disabled to allow more load carrying capability.

3.1.1.3 Distance Relays

Distance relays are energized by VT voltages and CT currents. The standard voltage ratings, maximum continuous voltages, and standard current ratings for the relays are specified by the above standard. The maximum continuous current is not specified and it varies from relay to relay. Typical values of maximum continuous currents for distance relays are usually 2-3 times rated nominal current.

The load limit for distance relays is covered in clause 2 “Fundamental Concepts of Loadability”.

3.1.1.4 Directional Power

Directional power relays can be applied on intertie lines between utilities, or between a utility and non-utility generation. These relays measure voltage and current and then calculate real power (watts), usually to limit power transfer due to line thermal limitations or commercial purposes. The basis for the setting of the relay becomes the load limit for the line.

3.1.1.5 Thermal Replica

Thermal replica relays emulate as closely as possible thermal processes in a protected system element. Practically, they are implemented exclusively as microprocessor-based relays utilizing currents, a temperature probe input, and a thermal and physical model of the transmission line aimed at calculating the hottest spot temperature based on available data in order to cause alarms or to trip. This type of relay uses current magnitude, and may also use other parameters such as the physical properties of the conductor, the effects of solar heating, the estimated wind speed across the conductor, geographical location (longitude and latitude), ambient temperature (measured), date, and time of day. Since the velocity and the direction of the air flow in the proximity of the line has a significant effect on the temperature of the conductors and due to the potential for variation of these factors along the line; several critically located sensors would be

needed. In the absence of these sensors and the communication system needed to consolidate that data from the sensors, assumptions must be made and margins used to allow for the errors in those assumptions.

3.1.1.6 Fault Detectors

Fault detectors refer to instantaneous overcurrent relays (usually non-directional) that supervise the operation of distance relays. In electromechanical schemes, the pick up of the fault detectors should be set above load to prevent contact wear due to chatter when the current is near pickup. Fault detectors can be set below load for multifunction microprocessor relay applications.

Some complex relays use the trip-supervising fault detectors to also serve as the fault detectors for the switch-onto-fault (SOTF) protection. When closing a breaker into heavy line loads, this can cause false (SOTF) trips if the fault detectors were set low enough to pick up. In this case, SOTF should be supervised by additional logic, such as undervoltage, to prevent false operation upon picking up load.

Some fault detectors used in microprocessor-based relays utilize the zero- and negative-sequence currents, sense the incremental positive sequence current (increase with respect to certain historical values), as well as adjust the threshold for the absolute current levels using an adaptive slow-acting control loop. Such improved fault detectors used to supervise the distance elements may prevent some false operations due to heavy loading.

3.1.1.7 Remote Breaker Failure Backup

At times, the protective relays on a line may be set to provide backup protection to lines leaving the remote bus. The increased relay reach required to provide this coverage will reduce the loading permitted by the relays. The installation of breaker failure and secondary relaying on those remote line terminals may reduce the need for remote backup allowing for shortened relay reaches and greater load capability on the line.

3.1.1.8 Local Backup Relaying

Local backup may be viewed as a secondary relaying system that provides backup for a failure of the primary relaying system. This secondary system typically is set identical to the primary so load limits are not affected unless the secondary relay has a characteristic that is more susceptible to tripping on load. This system does not cover the failure of a local interrupting device.

Another form of local backup is the protection for a failure of the local breaker or for a failure of the complete relay system. Also, as mentioned in the previous clause, local breaker failure relaying provides a means to isolate the fault 'locally' thereby reducing the need for a long reaching (and possibly load limiting) remote backup relaying settings. The fault-detecting relay that is used in the local breaker failure scheme is normally not the load limiting device.

3.1.1.9 Overload Protection of Tie Lines

Unscheduled outages can be a problem with major intertie transmission lines. When such a line is removed from service by fault or otherwise, the power flow through the rest of the system will likely persist. It is at such a time that overload conditions on other tie lines and internal lines could occur.

Occasionally overcurrent relays are used to protect tie lines from overloading. When power flows increase drastically, overload relays can help prevent damage to transmission lines and other equipment. The overcurrent relay characteristics have to be based on both time and current to prevent false tripping due to

short term transient load excursions. The overload relays must carry maximum load during short time or emergency conditions, without tripping.

It is not always the line on which the overload relays are installed that could be damaged. Shedding tie line load may prevent overloading of other transmission lines and equipment in the system. Occasionally the overload sensing of a transmission tie line is used to transfer trip a transmission line or other equipment in some other part of a system, and vice versa.

3.1.2 Pilot Systems

Line loading can cause a problem for a specific case of blocking carrier. In a directional comparison blocking scheme on a three-terminal line, outgoing load can pick up the reverse zone relay on one terminal, thereby sending carrier to block the other two terminals. If that terminal with outgoing load is a weak fault current source, a fault on the protected line may not drop out the picked-up blocking. In that case, the other two terminals of the line would remain blocked and will not pilot trip for the fault.

In phase comparison blocking schemes, current-based fault detectors key carrier at one current level and arm the comparison tripping logic at a higher current level. Sufficient load to key carrier, but not arm tripping, will not present a tripping risk, but will operate the carrier and may bring in alarms for sustained carrier keying. Load through the line (appearing like an external fault) above the comparison tripping level presents a risk of false trip if the blocking carrier function does not perform correctly each half cycle. This applies to two or three-terminal lines.

3.1.3 Current Transformers

3.1.3.1 Thermal Limits

The CT ratio should be selected so that, for maximum primary load current the secondary current produced does not exceed the continuous thermal current rating of any part of the CT overall secondary circuit. Most CTs have a nominal continuous current rating of 1- or 5- secondary amperes, but higher ratings can be specified. These ratings are specified by the standard rating factor. Values of the standard rating factor are 1.0, 1.33, 1.5, 2.0, 3.0 and 4.0 [2]. Cables and wire leads will usually have a greater ampacity than the CT secondary because other considerations determine cable and wire size.

3.1.3.2 Error

Maximum CT ratio error occurs during fault current, not load current, so CT ratio error is not a significant issue in affecting loadability. However, some low ratio protection CTs may have errors of a few percent even at load currents. CT accuracy will not be an issue if load limiting relays and meters are connected to the same CTs. However, if the relays are connected to high accuracy CTs and the meters are connected to low accuracy CTs, the relays may "see" currents a few percent higher than the meters. In such cases, lines operating close to load limits of relays may actually be operating somewhat closer to the relay limits than indicated by the meters. The effects of such CT errors along with other metering errors should be accommodated in the margins discussed in Clause 2.2 of this paper.

3.2 System Factors

3.2.1 Transmission Line Ratings

In the current market environment, utilities are pressured to use the capability of their transmission lines to the fullest extent by taking advantage of short term ratings, less conservative assumptions, and dynamic

ratings. Relays and their associated settings should be applied with both objectives of protecting the transmission line and making available the full capacity of the line.

Ratings of overhead transmission lines depend on the maximum temperature which the associated conductors may reach without exceeding clearance or conductor thermal damage limits. When an increase in current flow occurs on a conductor, its temperature change follows a time curve determined by the amount of current change, ambient conditions, and properties of the conductor. Ambient conditions include wind speed, air temperature, amount of cloud cover, angle of sun in the sky, and various other parameters of the surrounding air.

3.2.1.1 Continuous Rating

In Figure 2, I_1 and Temp 1 represent less than critical flow, with a dynamic change to I_2 and Temp 2 at critical flow. If Temp 2 represents the limiting or 'critical' temperature for which a line is designed, then I_2 would represent the continuous rating of the line and could flow indefinitely. This rating is sometimes referred to as the 'normal' or '24 hour' rating. Line ratings are typically expressed in amperes or MVA.

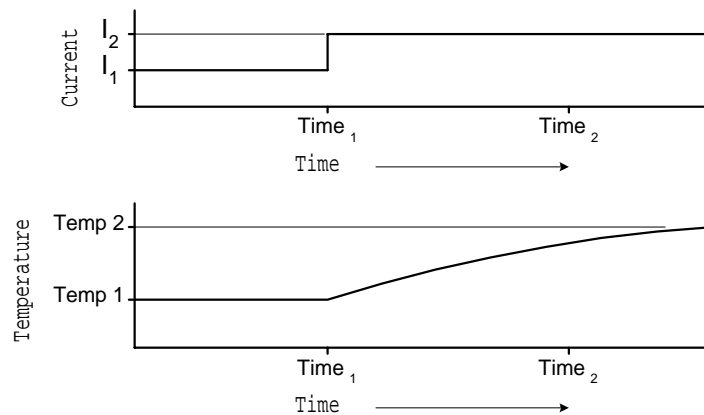


Figure 2: Critical temperature rise for the continuous rating of a line

3.2.1.2 Short Term Rating

When the current increases are of short duration, a higher current level can exist without exceeding the critical temperature limit. A typical 'short-term' temperature rise characteristic is illustrated in Figure 3. Short term or 'emergency' ratings of lines are established to identify the level of overload that can be carried by transmission lines during short time frames which typically vary from several minutes to several hours.

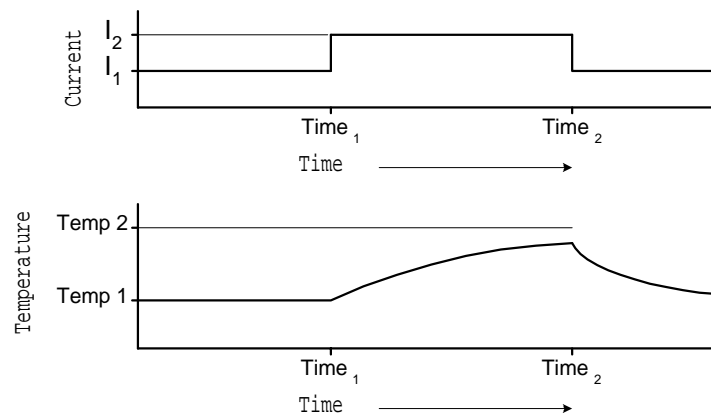


Figure 3: Typical temperature rise for determining short term ratings

3.2.1.3 Seasonal Ratings

Since the conductor temperature rise is dependent on ambient temperature, different ratings can be established from a seasonal standpoint on the basis of expected ambient temperatures using probabilistic historic data. Summer and winter ratings are typically established. In the same way, day and night ratings can also be developed.

3.2.1.4 Dynamic Ratings

The above rating methods are static in nature and are embedded with conservative assumptions to allow for 'worst case' conditions. Dynamic ratings are based on actual prevailing conditions as they exist at a given time and, as such, are typically higher than related static ratings. Determination of line ratings on a dynamic basis requires real time continuous monitoring of parameters such as conductor temperature or line tension.

It is possible that static ratings of other equipment connected in series with a line such as circuit breakers, switches and line traps may be less than that of the line itself. In such cases, the facility with the lowest rating will determine the maximum load that can be applied to the line.

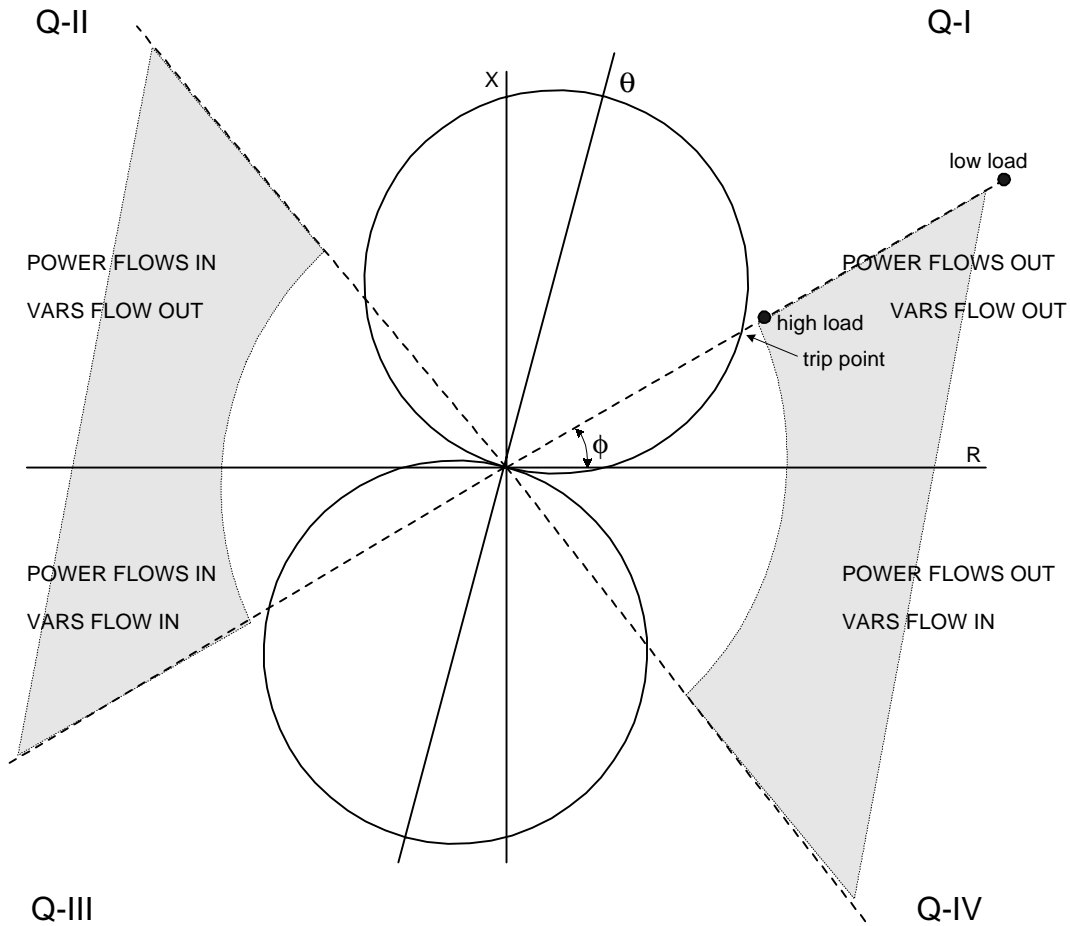


Figure 4: Load vs. trip point on R-X diagram

3.2.2 Transmission System Power Factor

Load is practically viewed as MW and Mvars, which can be converted to impedance and plotted as a point on an R-X diagram as shown in Figure 4. The shaded areas show typical load regions. Lines can be operated with the apparent load impedance in any of the four quadrants of the R-X plane. (e.g. Quadrant I: REAL POWER FLOWS OUT, VARS FLOW OUT) As load increases, the apparent impedance decreases, thereby moving the load impedance point toward the origin, and closer to the mho circle trip characteristic.

The angle of the load current (power factor angle) determines the angular location of the load impedance point and at what angle ϕ it would contact the mho trip circle. Power factor (PF) angles typically range from zero degrees to +/- 40 degrees, compared to the relay characteristic impedance angle θ which typically ranges from 60 to 80 degrees. As shown in Figure 4, the power factor angle affects the loadability. For example, in Quadrant I (POWER FLOWS OUT, VARS FLOW OUT), as the PF angle increases, the load which can be transferred decreases. One must also be aware of load in the reverse direction (Quadrants II and III).

For long reaching mho settings, some utilities assume the worst case of the load angle equal to the relay angle. Others take advantage of a more reasonable assumption such as 32°, 30° or 26° lagging load. For

example, this can provide as much as 37%, 41% or 52% increased loadability, respectively, compared to using a relay angle of 75 degrees as the load angle.

3.2.3 Unbalanced Currents

Unbalanced load currents present additional challenges to transmission line protection systems. If one phase is more heavily loaded than the others, the relay load limit on that phase (due to overcurrent, impedance or mho relay limits) will result in a lower three phase load than could have been transmitted if all three phases were balanced. Unbalanced load current also results in zero sequence or negative sequence currents that may appear as faults to sensitive protection that responds to such quantities. It should be noted that even though the load presented to a transmission system may be balanced, unbalances in the system impedances may result in unbalanced load currents. Unbalanced system impedances are most often caused by untransposed transmission lines. The unbalanced currents resulting from such unbalanced impedances generally become more of a problem as loads become very heavy or if unbalanced settings are too sensitive.

Most conventional fault study and power flow analysis computer programs usually assume the power system is completely balanced. Special analytical tools are required to represent the system on a phase by phase basis to examine the effect of load and system unbalances. Such tools include electromagnetic transients programs (that perform steady state analysis on a phase by phase basis), and specially written analytical routines on commercial graphic analysis/mathematical programs. These special tools are not normally used on conventional protective relay applications. Therefore the first indicator of a load balance problem affecting line loadability is usually undesirable line tripping during heavy loads. Digital relay event records that include pre-trip recordings will assist in the identification of such unbalances. Multifunction digital relays may also have spare unbalance current level detectors that could be used to generate an alarm if sustained unbalanced load current approach the limits of unbalance protection. These alarms may be used to identify approaching load limits due to unbalance before the limit is found by line tripping.

One solution to the potential misoperation of neutral and negative-sequence overcurrent relays under overload unbalanced conditions is to use positive sequence restraint. A portion (from a few percent up to about 15%) of the positive sequence current magnitude is used to compliment the negative- and zero-sequence operating currents. As the load increases, the zero- and negative-sequence currents caused by line asymmetry increase, but at the same time, the positive-sequence current increases as well providing restraint to prevent false tripping.

3.2.4 Multi-Terminal Lines

Transmission line loadability creates additional challenges to adequately protect all terminals of a multi-terminal line with standard relay reach and time settings. The transmission line protection system must allow maximum load to flow during short time or emergency conditions without tripping.

The apparent line impedance, as seen by the protective relay can drastically increase due to infeed currents. It is the effect of the apparent impedance that necessitates the need for high impedance settings, which in turn infringes on loadability of the multi-terminal line.

Typically Zone 2 elements are set to protect all terminals of a multi-terminal line with the worst infeed conditions. This means sensing a fault at any terminal and tripping in a definite amount of time. When the load-carrying level has to be preserved and the distance relay settings cannot be set to protect to the end of each terminal in a reasonable time, other means must be taken to ensure adequate protection. Sequential tripping or pilot systems can usually solve these problems. With sequential tripping, tripping speed is

sacrificed. This slower tripping has to be weighed against all other factors. The use of a pilot system can usually solve the problem, but is often the most expensive solution.

3.2.5 Power Swings

The apparent power flow of a typical transmission line, whose impedance is predominately inductive, is determined by its reactance and the magnitude and angle of its terminal voltages.

$$P = \frac{V_s \cdot V_r}{X} \cdot \sin \delta \quad (4)$$

where,

V_s , V_r are the magnitudes of the sending and receiving end voltages.

X is the line reactance.

δ is the angle by which V_s leads V_r .

Any disturbance to the power system, such as a fault, a load change, or line switching, causes the relative angular positions of the power generators to change. Because of the inertia of the generators, these changes are oscillatory; the angles overshoot and swing around before settling down to their new positions. These generator angle swings cause changes in the angles of the line terminal voltages and result in power flow swings on the lines.

For lines subject to significant power swings, loadability studies must be concerned not only with the maximum steady-state power flow, but also with the magnitude and duration of power swings. Protective relays must refrain from operating during stable swings, otherwise unnecessary tripping of sound lines will aggravate the disturbance.

For example, in Figure 5, the line current swings above the pickup level of an overcurrent protective function three times before settling to a new operating level below the overcurrent setting. If the integrated time above the pickup level exceeds the relay setting, an unwanted trip will result.

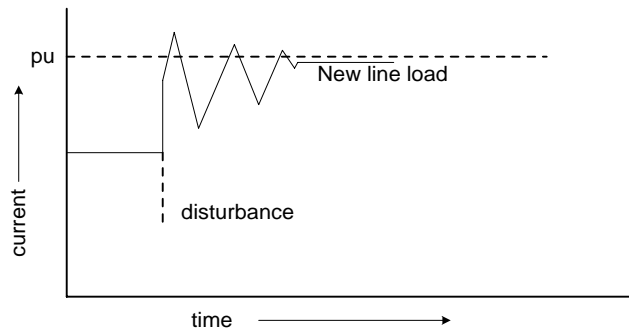


Figure 5: Line current swings

In transmission systems, distance relays are more common than overcurrent types and swings can be plotted on an R-X diagram to determine their proximity to relay characteristics.

If a line is near the electrical center of the swinging system, the apparent impedance seen by the line's distance relays may enter the relay characteristic during power swings. (Figure 6) If the apparent impedance remains within the characteristic longer than the time delay setting of the zone, an unwanted trip

will occur. A transient stability study of the system is usually necessary to determine the locus of apparent impedance during such disturbances.

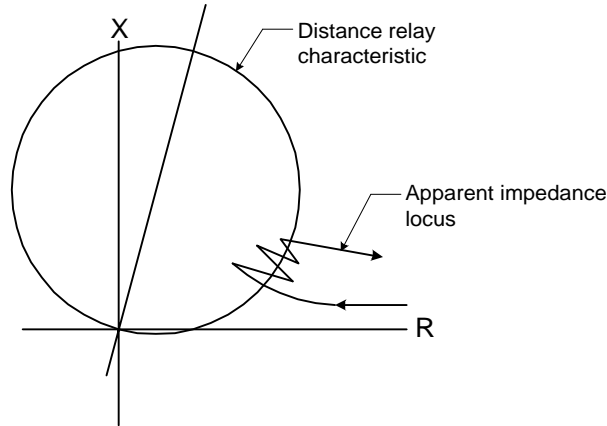


Figure 6: Apparent impedance for power swing

Long and heavily loaded transmission lines between load and generation centers are generally much more vulnerable to such problems than short, metropolitan-area lines between load stations. When there is a risk of unwanted tripping during stable power swings, auxiliary protective devices providing power-swing blocking (also known as out-of-step blocking) may be used to ensure security of the distance relaying.

3.2.6 Faults and Fault Angles

In addition to power swings discussed in the previous clause, other factors may affect a relay's performance during certain load flow conditions. Depending on the type of relay characteristic, load flow combined with fault resistance may result in incorrect operations for remote end faults and for reverse faults.

For the representative system shown in Figure 7, assume the load flow is from left to right. Then, Figure 8 shows that the sending end voltage (V_S) progressively leads the left bus voltage (V_{BL}), the right bus voltage (V_{BR}), and the receiving end voltage (V_L). Now, consider relay R1 at the left bus and assume that a fault occurs just beyond the right bus as shown in Figure 7. The fault current from the left end of the line will be derived from the voltage of the sending end source and the impedance to the fault. The angle of the pre-fault voltage at the left bus and the sending end source voltage will be different by the load flow angle. Thus, the angle between the left bus voltage and the current will be different from the true fault angle during the time that the pre-fault voltage is maintained by memory action.

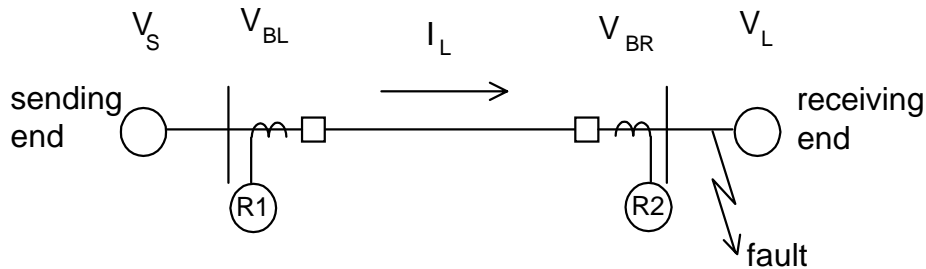


Figure 7: Representative system

The condition described above may have a substantial impact on the apparent impedance of a distance relay. With pre-fault loading and non-zero fault resistance, the apparent impedance will be different from

the actual positive sequence impedance to the fault. Depending on the type of relay characteristic (mho, reactance, quadrilateral), the type of fault, and the direction and magnitude of the load flow, the effect could create an underreach condition or an overreach condition.

Another condition that could create an incorrect operation is a close-in reverse fault. Consider relay R2 at the right bus and assume a single-line-to-ground fault with fault impedance at the right bus as shown in Figure 7. Figure 8 shows the resulting pre-fault voltages with the assumed left to right load flow. In this case, the source voltage (V_S) driving the fault current will lead the initial polarizing voltage of the relay. Although the dynamic coincidence angle calculated by the relay results in a non-trip condition, the steady-state angle between the relay operating voltage and polarizing voltage will be less than 90° . For some relay designs, this polarizing angle error can cause incorrect operation on reverse faults.

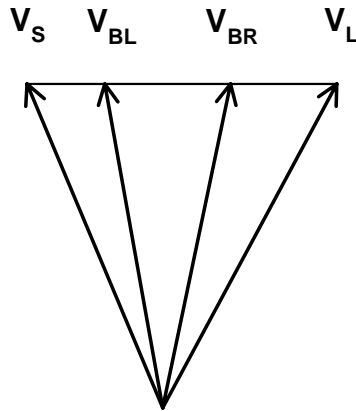


Figure 8: Prefault voltages

In any case, the possibility of operating for an external fault during heavy load flow is extremely undesirable. This operation could remove unfaulted equipment from service when the system is already stressed to its limit. Certain relay designs have found ways to reduce the undesirable effects of load flow on relay performance. The protection engineer should look for cautions in the relay manufacturer documentation related to load flow and settings. To independently determine the amount and extent of the overreaching on particular relay designs, dynamic testing may be necessary. This testing may be needed to determine if the steady-state margins generally applied to load encroachment on protective relays are adequate for a particular zone of protection.

4. Solutions

4.1 Relay Settings

One significant solution to relay loadability issues is the selection of relay settings. The pickup of the relay as well as the characteristic shape of the affected element can, in most cases, be varied by changing the settings of the relay. The following is a discussion of how the relay settings can be varied to deal with loadability issues.

4.1.1 Line Coverage

Desired line coverage by distance elements is influenced by many factors including the protection scheme being used, the measuring characteristics of the relay elements and system configuration. The chosen

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protection schemes using distance elements can include non-pilot stepped zone schemes as well as any of several underreaching and overreaching directional comparison pilot schemes. The characteristic of the distance elements in use can be one of several different types including impedance, mho, offset mho, reactance, quadrilateral and lenticular. Due to the varying shapes of these elements, a setting to obtain the desired reach at the line impedance angle can result in varying sensitivities to load encroachment. System configuration has a large effect on the settings required in these schemes to get effective coverage. Line length, number of line terminals, distribution transformer line taps and infeeds can all require overreaching elements to be set quite long. Obviously, the longer the required relay reach, the more likely a loading problem can occur.

Using the equation:

$$S_{max} = V_{LL}^2 / Z \quad (\text{where } Z \text{ is the relay reach}) \quad (5)$$

gives a conservative estimate of whether the relay settings will pose a problem or not.

A typical transmission line may employ up to three or more zones of protection for multi-phase faults. These zones may be employed in a high-speed pilot type protection scheme or in a stand-alone back-up scheme or in portions of both schemes.

4.1.1.1 Forward Zones

Underreaching elements such as zone 1 rarely encounter a problem from load. If a loading problem were found to exist for zone 1, the reach can usually be shortened to eliminate it. If zone 1 is used in an underreaching pilot scheme, an overlap of the opposite zone 1 settings must be maintained. A zone 2 element is always required to reach the remote bus with a least a 20-30% margin. Setting zone 2 at this minimum reach will not exceed the load limits in most cases of two terminal lines. Other overreaching zones require much longer settings and are therefore susceptible to loading problems. They generally exist to provide remote backup protection and tripping sensitivity. These zones along with multiterminal zone 2 settings must accommodate infeed conditions which cause an increase in the required reach. If loading is a problem for the overreaching zones they may be eliminated if their role of backup relaying is not considered crucial. Otherwise, the loading problem must be handled using a selection of relay characteristic shapes, blinders, load encroachment settings, or other solution.

4.1.1.2 Reverse Blocking Zones

In a directional comparison blocking scheme a reverse looking distance element is used to send block to the remote terminal. It is set to reach behind its terminal and overreach the remote tripping relay by an adequate margin. Because of the element's reach, it can be susceptible to load encroachment. If this element is only used to send a blocking signal to the remote terminal it will not directly cause the line to trip due to load. The element could delay or prevent tripping for internal line faults that would have other adverse consequences. In some schemes the reverse blocking element also trips through a timer for backup protection. For these schemes, tripping would occur as a result of load encroachment.

4.1.2 Backup Coverage

For lines with three terminals or lines with taps for distribution transformers, the effects of infeed and apparent impedance cause overreaching Zone 2 and Zone 3 impedance settings to be increased. This also causes reverse blocking impedance settings to be increased. As a result, these elements are the most susceptible to load encroachment.

4.1.3 Breaker Failure

In order for the breaker failure overcurrent fault detection to be sensitive enough to cover at least the protected line, it is often necessary to operate with the detector picked up constantly at times of heavy load. This is not usually a problem as long as the breaker failure relay time delay is initiated by protective relay tripping and adequate time is provided to allow overcurrent fault detector to reset after the breaker interrupts the fault. The specifications for the fault detector relay should be checked to make sure that the level of load current does not exceed the continuous rating of the relay.

4.2 Dealing with Transients

By definition, transients are short time phenomena. If the transients result in measured parameters that enter the operating characteristics of an instantaneous relay, it will trip. If the parameters enter the operating characteristic of a time delayed relay it will trip only if no other protection or control action is taken to move the system conditions outside the characteristic. The dual approach for line protection dealing with transients is to ensure that:

1. Measured parameters do not enter the operating characteristic of instantaneous protection
2. Time delayed protection is coordinated with other protection and control systems which are intended to relieve the transient condition to an extent where the measured parameters do not enter the relay's operating characteristics.

The following will consider the various measured parameters that may affect line protection systems.

4.2.1 Voltage

Transient voltage depressions usually have more significant effect on line protection systems than transient overvoltages. Voltage depressions are often an indicator of a stressed or faulted system. If they are caused by a faulted system, proper time coordination of the main and backup protection systems will ensure satisfactory operation. However, if the voltage depression is caused by severe overloads, special protection systems, or operator action will normally be required to deal with the problem. The line protection system will:

- a.) either have to coordinate with special protection systems (if they exist),
- b.) or be applied, and set, such that the maximum voltage depression during transient overload conditions will not cause the measured parameters to enter the operating characteristics of the line protection system.

This second requirement means that protection systems should be applied and set such that the steady state operating characteristic will not respond to voltage depressions during heavy overloads for which no automatic remedial action is expected. It should be noted that low voltages on transmission systems are often accompanied by high reactive power consumption that may cause the power factor of the load impedance to take on an unusually low value. Figure 9 from [6] shows the change in apparent impedance in two different types of load ((a) and (b)) as the voltage is varied from 1.1 p.u. to 0.8 p.u..

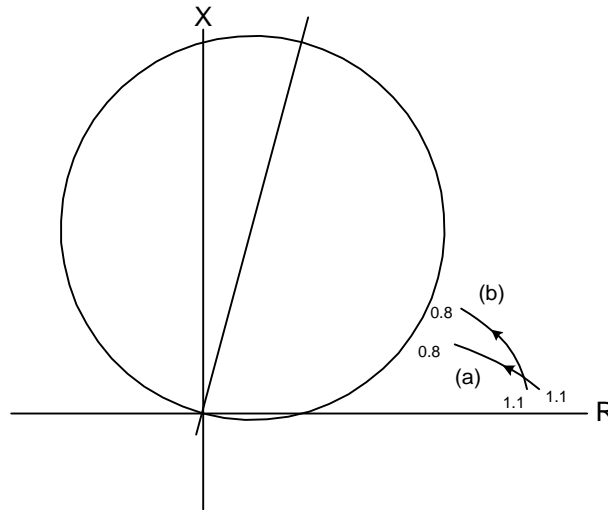


Figure 9 - Change in apparent impedances due to voltage changes.

It can be seen from Figure 9 that the change in apparent impedance is very dependent on the relationship of load impedance to voltage. One phenomenon that can cause significant voltage depression is that of stalling motor loads. Motors may stall due to slowly cleared faults [4] or slow voltage recovery following fault clearing. The increased reactive power drawn by stalled motor loads can depress transmission voltages and cause load impedances to enter the characteristics of long reaching distance relays.

The use of a lower than normal voltage (1.0 to 0.8 p.u.) to calculate the load limit of the distance relays; $S_{max} = V_{LL}^2/Z$, clause 2.2.2; will compensate for the undervoltage condition that could occur with an overload condition.

4.2.2 Thermal Load

Thermal overload conditions may or may not result in voltage depressions, but are the result of unusually high currents. Transmission lines are often able to withstand moderate overloads for several seconds, or even minutes. Although short circuit protection is sometimes set to protect a line from overload, it is not the best way to provide such protection. Short circuit protection (such as Zone 3 elements of distance relays) can never be expected to coordinate with the thermal overload capability of transmission lines. If lines are expected to be able to sustain temporary overloads, either adequate operator control should be ensured, or specifically designed thermal overload protection should be applied (see clause 3.1.1.5). The thermal overload protection should be able to coordinate as much as possible with the temporary overload capability of the protected line.

4.2.3 Load Angle

Very heavy loads resulting in high load angle across a transmission line may cause certain types of distance relays to become blind to remote phase to phase short circuits[3]. In this situation, the security of the line protection is not threatened as much as the dependability to sense all faults in the protected zone. For this reason, transient conditions that result in a high load angle, without associated voltage depression or thermal overload can usually be tolerated until operator action can reduce the load angle.

4.2.4 Outages – Three Phase and Single Phase

Transmission line outages due to temporary faults are usually restored to normal by automatic reclosing. Tripping may be single phase or three phase.

In the case of three phase tripping, parallel circuits may be temporarily overloaded, or may be subjected to reduced voltages or high load angles or swings. In such cases, the comments noted above regarding those transient conditions become applicable.

In the case of single phase tripping, the faulted line is still able to carry a portion of load, and possibility of problems due to high (balanced) load in parallel circuits is reduced. However, while the single phase is open, the surrounding power system is subject to a certain amount of unbalance, and line protection in adjacent or parallel circuits (such as negative or zero sequence overcurrent protection) may misoperate due to the unbalance resulting from load flow through the faulted line [5].

In such cases, the sensitive unbalance protection must be time delayed to coordinate with the reclosing and maximum expected pole discordance time of the line with single phase tripping.

4.3 Protective Equipment

There are several features and options that may be available in protective equipment which can allow a protective device to be less sensitive to load current while still providing the desired fault protection settings.

4.3.1 Distance Relay Characteristic Shape

A lenticular, rectangular, or even more sophisticated characteristic enables a relay to protect the line, provide maximum resistive fault coverage, and still avoid overlapping with the load regions on the impedance plane. This applies to underreaching zone 1, as well as to overreaching zones 2 and 3, and the reverse zone used by distance blocking pilot schemes and for remote breaker failure. Appendix B discusses the different characteristic shapes in more detail.

4.3.2 Use of blinders

A blinder is an element of a distance relay that can be used to restrict the operating characteristic of the relay. One common blinder is a straight line characteristic on the R-X diagram and generally at an angle from 60 to 90 degrees positive from the R axis. The straight line is positioned to limit the resistive reach of the distance relay. Another type of blinder has a more complex characteristic that restricts the operation of the distance relay in an area near the R axis. Both types of blinders are typically used in combination with a mho characteristic. The combination of the mho characteristic and a blinder is set to protect the line and limit the area of tripping for steady state conditions in the region of load and therefore reducing the limitation the distance relay would have on line loading. Figure 10 shows both types of blinders applied with a mho relay. Typically only one type of blinder would be used in a given application.

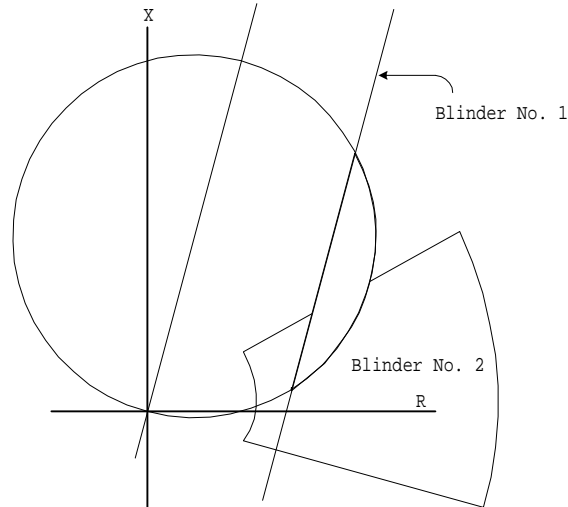


Figure 10: Blinder characteristics

If the mho and the blinder characteristics are produced by two different relay functions the combination may have different reaction times to changing fault and load conditions. The transient reaction of the combination may lead to greater difficulties with transient overreach for a fault just beyond the length of the line with previous heavy load flow. Care must also be taken that a stable fault swing after heavy load flow does not activate a mho relay implementing blinder characteristic. Creating both the mho and blinder characteristics with algorithms in a single microprocessor relay removes this concern.

4.3.3 Power Swing Blocking

Transmission line distance relays are susceptible to tripping on stable and unstable swings where the apparent impedance presented to the relay enters the operating characteristic. Where operation of the line protection due to swings could cause undesirable consequences, the protection may be supplemented by additional protection (out-of-step protection) to detect the swing condition. The out-of-step protection is usually set to detect the swing before the short circuit protection would operate. The out-of-step protection may be used to block the distance protection and/or to trip the line at an optimum line angle. When out-of-step protection blocks a line trip, it should be ensured that the out-of-step condition will be eliminated by some other means of separating the two asynchronous sources. Thus out-of-step blocking is often only applied in association with out-of-step tripping at some other preferable separation point. (see clause 3.2.5)

Transmission line protection systems that depend on a phase comparison or differential protection technique will not sense swings that are centered in the protected line. Out-of-step tripping protection may be used to supplement differential or phase comparison protection where line opening on an out-of-step condition is required.

A typical out-of-step blocking scheme uses two separate regions on the impedance plane and monitors the timing of the apparent impedance entering the two regions (outer and inner). Fast movements indicate a fault, slow transitions indicate a power swing. The problem is that the two zones must have finite size difference. The outer region may overlap with the region of increased load. A distance relay with out-of-step blocking will require more room to keep its out-of-step outer zone between the regions of increased load and inner line impedance.

4.3.4 Adaptive techniques

In many microprocessor-based relays, settings can be changed using setting groups to accommodate system conditions (e.g. load level, generators or lines in/out of service). At the present time, adaptive techniques that automatically modify settings according to measured system conditions have not been widely used.

4.4 Systems

Loadability must be considered when designing an overall system. All aspects of the design, the operations, the automatic systems, and the protection system must coexist and work together to fulfill the overall design criteria. The intent of the transmission planners, the purpose of the operating constraints, and the protection system limits all have to be considered when trying to satisfy a loadability limit.

4.4.1 Planning

With respect to transmission line loadability, it is prudent for the design of a protection system to be closely coordinated with the planning of transmission facilities. If additional terminals to the surrounding transmission network were proposed to be added to a transmission line, the proposed terminals will introduce short circuit current infeeds to the line. If a transmission line is protected by a directional comparison pilot protection system supervised by impedance elements, the new terminals will necessitate an extension of the reaches of these impedance elements. If this extension of impedance relay reach results in an undesirable decrease in line loadability, then another type of protection system (i.e. phase comparison instead of directional comparison) must be considered.

4.4.2 Controlled Flows on Lines

Reconfiguring the power system can often control load flows to reduce an overload condition on a transmission line. Phase shifting transformers or other modern flexible ac transmission technology techniques may also be used to control the load flows on transmission lines.

4.4.3 Load Shedding

When transmission lines become severely overloaded, it may be necessary to shed load in order to maintain integrity of the power grid. Load shedding can be accomplished by manual load shedding, automatic load shedding (e.g. undervoltage load shedding), or via SCADA.

4.4.4 Series-Compensated Lines

Series Capacitors (SCs) have become an important element in economical long distance power transmission. The main purpose for using SCs is to decrease the effective inductive reactance of a power line. The following benefits can be achieved:

- increased power transfer capability (Figure 11).
- improved power system stability,
- reduced system losses,
- improved voltage control,
- better power regulation.

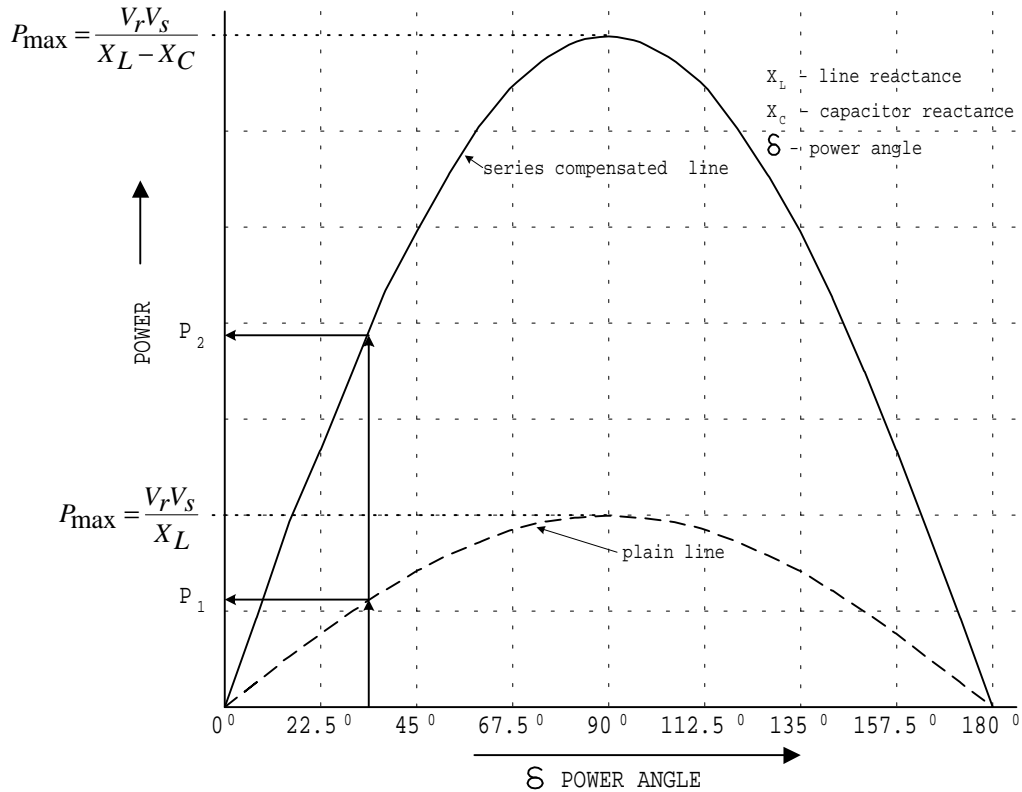


Figure 11: Comparison of the loadability of uncompensated and series compensated lines

The cost of increasing line loadability by installing SCs, compared to constructing a new equivalent line, is usually in the order of 15-30%. The amount of series compensation is typically limited to 60-70% of the line reactance in order to avoid undesirable subsynchronous oscillations. The series capacitance can be installed entirely in one location, either in the substation or someplace along the line (typically mid-line). Otherwise, the series capacitance is split between several (typically two) banks of capacitors installed at both ends of the line.

Series capacitors are normally equipped with both automatic and manually operated bypass facilities to protect the capacitors from overvoltage during faults and to enable operation of the line while the capacitors are out of service. Protective relaying for series compensated lines must be capable of accommodating the maximum power transfer with the capacitors in service, yet also be able to detect faults at the remote end of the line with the capacitors bypassed. Since series compensated lines are usually long lines, special attention is needed to be sure that the selected line protection will not limit the load transfer capability of the line.

5. Summary

The essential goal of relay system design with respect to loading is to ensure that no unintended relay operations occur during conditions created by system load. The fundamental definitions of relay load limits are discussed. Calculations of limits are covered for the most common relay types. Examples of calculations for overcurrent and mho impedance type relays are provided in Appendix A. These calculations are made to assure that the relays will not trip under maximum load conditions.

Beyond the fundamental issues, many factors that have the potential to limit loading need to be considered. Some of these factors are directly related to the relays. These include not only the settings, but also the choices of relays and relay schemes. Many system factors will also affect the application and performance of relaying systems. Included are line ratings, loading, power factors, load balance, and multiterminal connections. The effects of swings and faults are also included.

Once the problems related to loading are outlined and discussed, the next step is to begin to address them. The solutions discussed are accomplished through relay settings, selection of equipment, and design of schemes applied to prevent load problems on relaying systems. Many times, careful planning and control of the system operating issues can help prevent load problems from occurring.

6. Appendix

Appendix A: Overcurrent Relay Loadability Calculation Example.

The following is an example calculation of the loadability limit for a 60 kV line with a tapped maximum distribution load of 40 MVA plus transmission load through a remote terminal and with a phase overcurrent relay set to start at 800 A primary. It is assumed that the 800 A setting of the overcurrent relay cannot be increased due to the need to provide dependable protection for short circuits under all contingencies.

If a 50% margin is required to ensure the ability to pick up cold distribution load tapped onto the line simultaneously with the ability to carry transmission load (through the remote terminal of the line), and a 20% margin is required for the transmission load, the following loadability results are obtained.

The maximum distribution load current is

$$I_d = \frac{40,000}{60 * \sqrt{3}} = 385 A$$

The required allowance for distribution load current with 50% margin gives a need to allow $1.5 * 385 = 577$ A for distribution load.

Remaining allowance for through load = $800 - 577 = 223$ A

and allowing a 20% margin for through load, additional loadability for through load is

$$I_t = \frac{223}{1.2} = 186 A$$

And the total loadability for the line including margins for tapped 40 MVA distribution load and through load is then given as $I_d + I_t = 385 + 186 = 571$ A

A current of 571 A corresponds to approximately 59 MVA at 60 kV.

Thus the loadability of the line protection system could be stated as “571 A, or 59 MVA at 60 kV, including margins”. The loadability of the protection system could be of concern if it was lower than the rated loadability of the line.

Mho Distance Relay Loadability Calculation Examples

Example 1 Consider a mho distance relay with a maximum torque angle of 75° set with a reach of 100 ohms primary protecting a 230 kV transmission line. Assume it is not possible to reduce the reach setting of the relay, and no special load blinding characteristics are applied. Also assume that it is desired to calculate the loadability at the nominal voltage of 230 kV assuming a worst case load power factor of 0.866 (30° lagging) and with a safety margin of 80%. That is, the relay is not expected to reach greater than 80% of the minimum impedance presented by the load with a power factor of 0.866. If planning studies indicate that the overload condition could be associated with an undervoltage condition, a voltage lower than nominal should be used for the calculation.

Reach of relay at an impedance angle of 30° $Z_r = 100 * \cos(75-30) = 70.7$ ohms.

Minimum allowable load impedance is therefore $70.7 / 0.8 = 88.4$ ohms.

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Maximum allowable loading with margin, is $230^2 / 88.4 = 600$ MVA (approximately).

Example 2 A certain 138 kV line has recently been rated for 346 MVA under emergency or peak conditions. The company requires a 5% margin for relay pickup at 30 degree power factor. One end of the line has a relay with a forward looking mho setting of 90 ohms at 82 degrees. The setting is checked as follows:

$$Z_r = 90 * \text{COS}(82-30) = 55.4 \text{ ohms}$$

$$138^2 / 55.4 = 344 \text{ MVA (approximately)}$$

This value is below the desired rating of 346 MVA. Working backward using the 5% margin:

$$346 * 1.05 = 363 \text{ MVA}$$

$$138^2 / 363 = 52.46 \text{ ohms}$$

$$Z_r = 52.46 * \text{COS}(82-30) = 85 \text{ ohms}$$

The setting is being used as remote back up. A reduction in the pickup from 90 to 85 ohms can be accommodated without any serious problems.

Appendix B: Fundamentals of Distance Relays

Distance relays are a family of relays that determine whether or not the impedance from a relay location to a fault is within the operating characteristic of the relay. The relays accomplish this by using the magnitude of voltage and current, and the phase angle between the two. The characteristic of this relay type can be described using a resistance-reactance (R-X) diagram. Some of the distance relays are better at handling heavy line loads than others.

Since the first type of distance relays used were impedance relays, the terms distance relay and impedance relay are sometimes incorrectly used interchangeably. The basic impedance relay's characteristic when plotted on an R-X diagram is a circle around the origin. The relay is non-directional, so it was most often used with a directional unit. The combination of the impedance unit and the directional unit produces a tripping area inside the circle of the impedance unit that occupies all angles within the first quadrant and parts of those within the second and fourth quadrants. (Figure 12) This type of distance relay is more sensitive to heavy loads than other distance relays. The relay's sensitivity to faults on the protected line and its sensitivity to load in the forward direction are equal. (Note that the forward direction is here defined by current flowing from the substation where the relay is located.)

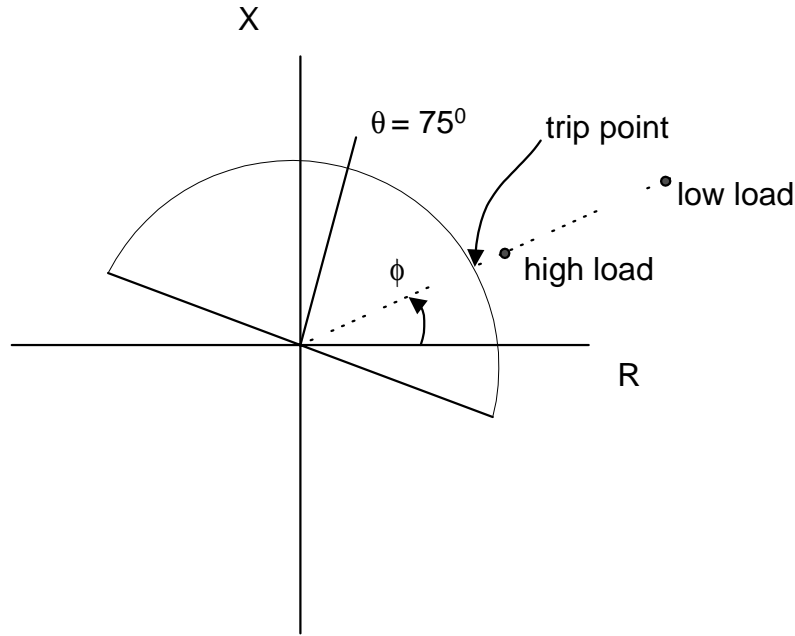


Figure 12: R-X diagram for directional impedance relay showing load vs. trip point

The offset impedance relay is a modification of the basic impedance relay. The characteristic of the offset impedance relay is a circle with the center offset into the first quadrant. (Figure 13) The chord of the circle that passes through the origin and the center of the circle is at the angle of maximum reach for the relay. This angle is set at or near the line impedance angle. If the line impedance is $R + jX$, the line angle is the arctangent of X/R . The higher the voltage of the line and the larger the line conductor, the larger the line angle.

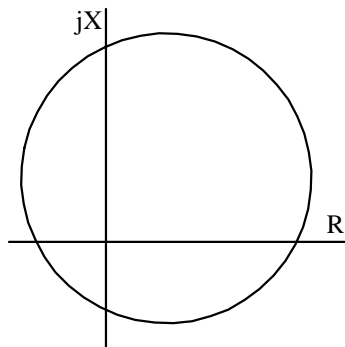


Figure 13: Offset impedance characteristic

Although the offset impedance relay is more sensitive in the forward direction than in the reverse, it still has some reverse sensitivity so it must be used with a directional unit or be time delayed. The decreased sensitivity of the offset impedance relay in the forward load area makes it better than the impedance relay for line loadability.

The mho relay reach characteristic is similar to that of a completely offset impedance relay. Its steady state characteristic is a circle that passes through the origin. (Figure 14) The maximum reach of the relay is set at or near the angle of the line impedance. No additional directional unit is required because the mho relay

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is inherently directional.. The reduced reach of the mho relay along the R axis allows greater loadability of the protected line than an impedance relay does.

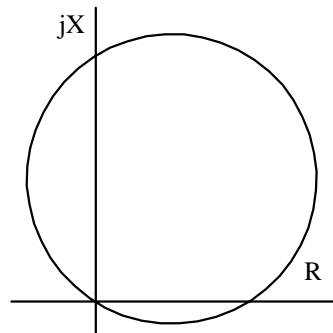


Figure 14: Mho characteristic

A reverse offset mho relay is a mho relay with the center of the circle offset in the direction of the origin. The offset mho relay, like the offset impedance relay, has a zone of sensitivity to faults in the reverse direction. The offset mho relay is applied in cases where it is important to include the origin in the trip zone and the unit is time delayed.

A forward offset mho relay is a mho relay with the center of the circle offset away from the origin. A forward offset mho characteristic can provide good backup protection for remote forward resistive faults, without the load encroachment problems of a mho element with no forward offset. Figure 15 shows a forward offset mho relay used in conjunction with a mho element.

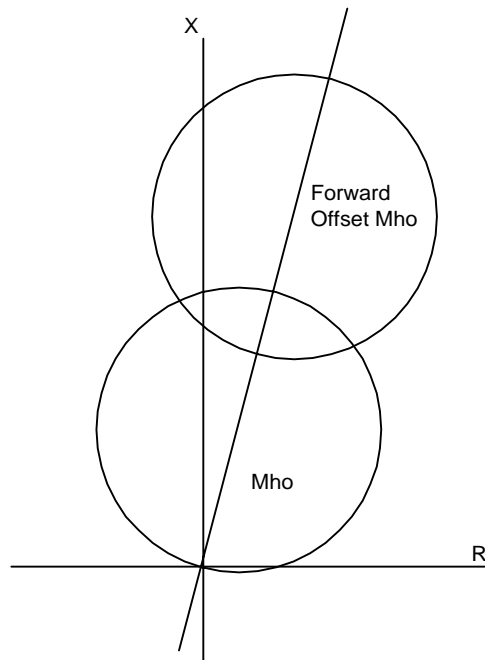


Figure 15: Mho and forward offset mho characteristics

For shorter lines the impedance and the offset impedance relays provide limited fault resistance coverage. For short line applications the type of distance relay called a reactance relay is used. The characteristic on a R-X diagram is a line drawn parallel to the R axis in the first and second quadrant. The distance the line is away from the R axis is determined by the setting reach of the relay. The reactance relay is directional but its reach in the resistive direction is only limited by the energy requirements of the unit. This makes the reactance relay very sensitive to load. To correct for this limitation, the relay is used in conjunction with a mho or an offset impedance relay to limit the resistive reach. (Figure 16)

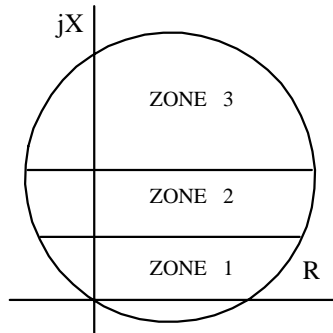


Figure 16: Self-polarized Mho and reactance characteristic

A variation to the reactance relay is a quadrilateral relay. With the quadrilateral relay the limit of its reach in the resistive directions are straight lines on a R-X diagram instead of using a mho element. (Figure 17) The reach in the area of forward load flow is limited by a discrete setting on the relay.

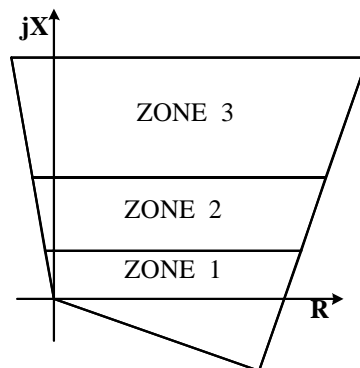


Figure 17: Quadrilateral characteristic

The mho relay characteristic can be described by measuring the angle between the operating phasor of $(IZ - V)$ and the phasor (V_{pol}) . Where I is the line current, Z is the reach of the relay at the maximum reach angle, V is the voltage at the relay location, and V_{pol} is the polarizing voltage. When the characteristic is defined by the angle being 90 degrees, then the characteristic is a circle. If the characteristic is defined by an angle between the phasors being greater than 90 degrees, the characteristic has a lenticular (lens) shape. (Figure 18) The lenticular characteristic allows increased loading on the line compared to the true mho relay but also has less sensitivity to faults with fault resistance.

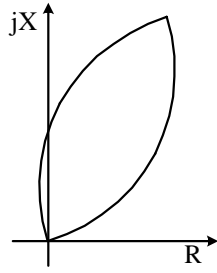


Figure 18: Lenticular characteristic

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