Overview of Series-Compensated Line Protection Philosophies

by

Finn Andersson
Relay Division
ABB
Västerås, Sweden

Walter A. Elmore
Relay Division
ABB
Coral Springs, Florida

❖

Presented to:

Western Protective Relay Conference
Spokane , Washington

October 23-25, 1990

Overview of Series-Compensated Line Protection Philosophies

by

Finn Anderson and
W. A. Elmore

Introduction

No relaying application has challenged the industry to a greater degree than the high speed relaying of transmission lines equipped with series capacitors. This paper will describe many of the pit-falls that exist in applying conventional relaying practices and will describe the extremes to which the manufacturers have gone to circumvent these problems. The paper will describe several of the types of relaying systems that have been designed with the series capacitor application in mind.

Introduction

Transmission lines are inherently inductive. The purpose of a series capacitor is to tune-out part or all of the transmission line inductance. In a network without series capacitors, faults are inductive in character and the current will always lag the voltage by some angle. Commonly used types of line protection can detect the fault, and by operating circuit breakers clear it fast and selectively. With the series compensation of the transmission line, capacitive elements are introduced, and the network will no longer be inductive under all fault conditions. The degree of this change is dependent on the line and network parameters, the extent of series compensation, the type of fault and the fault location.

The capacitive or apparent capacitive nature of the fault current may cause the line protection to fail to operate, or to operate incorrectly, unless careful measures are taken to acknowledge this problem. Due to the capacitive nature of the fault loop, the complication with respect to the protection may arise both on the compensated line as well as on adjacent lines.

Series capacitor banks are equipped with spark-gaps which bridge the capacitor, and often with metal oxide protective devices. The spark-gaps are set to flash over at a voltage 2-3 times the nominal voltage of the bank. When the spark-gaps flash over, the network is restored to an inductive nature. In spite of this, the protection complications remain. The spark-gaps do not flash instantaneously following the occurrence of a fault, and do not flash at all under some fault conditions. The time to gap-flashing is often longer than the operating time of high speed line protection. The effect of capacitive reactances must be evaluated even for faults which flash the spark-gaps. Adding to these complications is the fact that transients are generated due to the presence of the series capacitor at the occurrence of the fault as well as at the instant of spark-gap flashing.

The use of metal oxide devices in parallel with the series capacitor introduces another element of concern. These units are never removed unless they themselves are jeopardized. Their level of conduction is approximately 1.5 times the rated peak voltage of the series capacitor. When voltage in excess of their conduction level appears across the metal oxide device, their impedance reduces markedly causing the series capacitor to be partly by-passed. However, when the voltage decreases to a level below the threshold, the impedance of the device becomes very high, and the capacitor is effectively reinserted. This action provides another level of transient generation, but in general, causes a softer impact on the protective relaying than simple spark-gaps.

The metal oxide devices are bridged with triggered spark-gaps to limit the energy generated in the device during fault conditions. Therefore, the protective relays then must be able to handle the effect of both the metal oxide device and spark-gaps.

Relaying Quantities Under Fault Conditions

1. The effect of series compensation on transmission line protection depends on the location of the capacitors and the degree of compensation. Figure 1a shows an example of a one-line diagram of a series capacitor and a transmission line. Figure 1b is the "steady state" R-X (Resistance-Reactance)

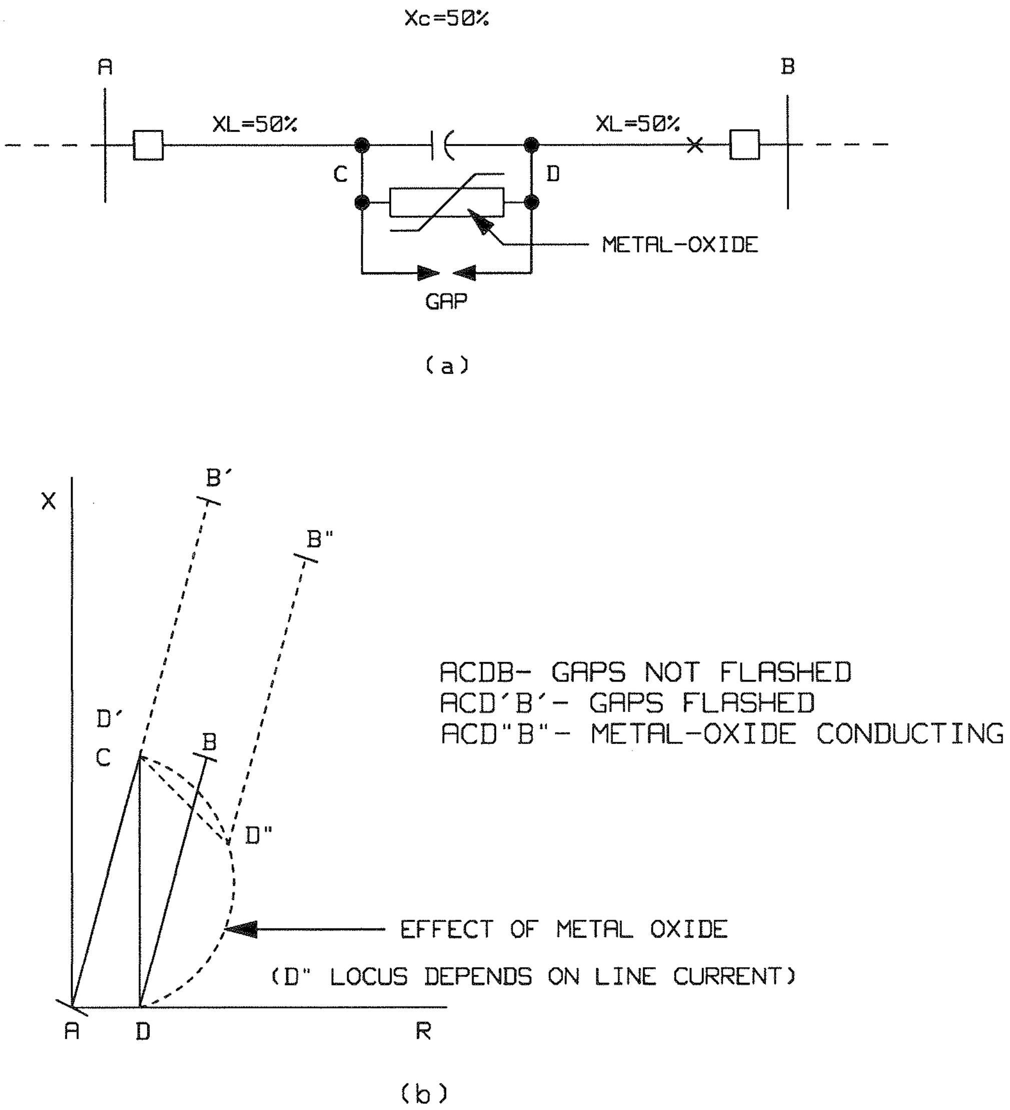


Figure 1. Apparent Impedance as Viewed from Station "A" for a Fault at B.

diagram. Because of the fact that the capacitor bypass protective equipment may be conducting or not, the apparent impedance as viewed from location A for a fault at B may appear vastly different.

2. Figure 2 shows the influence of a nearby series capacitor bank. Faults near the capacitor-line junction as viewed from location A will have a very large negative reactance character. This negative reactance is actually due to reversal of the voltage at the relaying point or under certain conditions reversal of the current through the series capacitor.

3. Voltage reversal occurs at the bus if the negative reactance of the series capacitor is greater than the positive reactance of the line section to the fault location. Current reversal occurs if the negative reactance of the series capacitor is greater than the sum of the source reactance and the line reactance to the fault location. Figure 3 shows this condition.

4. "Current reversal" can also occur in some applications where a fault is at the capacitor line junction and a parallel line exists between buses A and B. Figure 4 describes for a typical case, the variation of voltage to be expected at various locations in the power system. Note that there is no voltage inversion in this case. "Current inversion" occurs at 2. Current at 4, is also in the opposite direction to that for the same case without series capacitors. Whether line-side or bus potentials are used for the relays, makes no difference in establishing the direction to this fault.

5. As can be seen in Figure 3a the "zero" voltage point in the system can be moved farther back in the system as a result of multiple lines contributing to a fault near the capacitor-line junction. The negative reactance of the capacitor is enlarged compared to the positive reactance of one of the

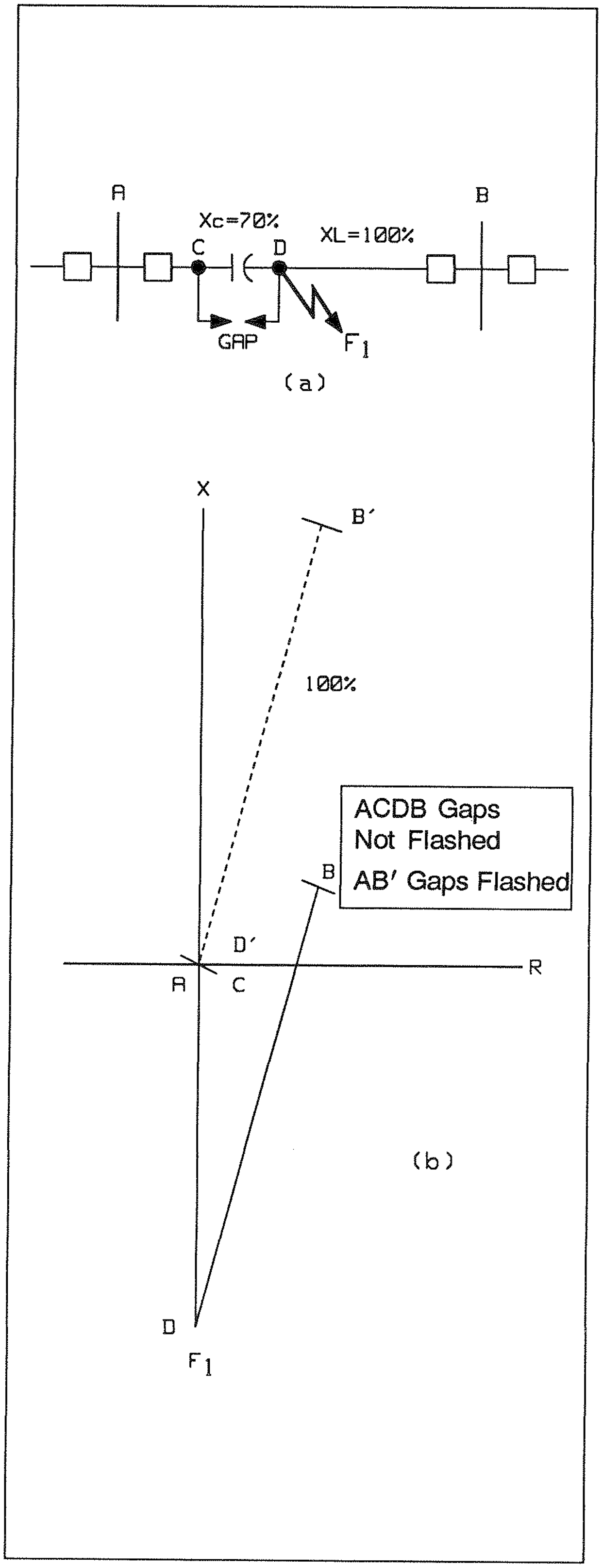
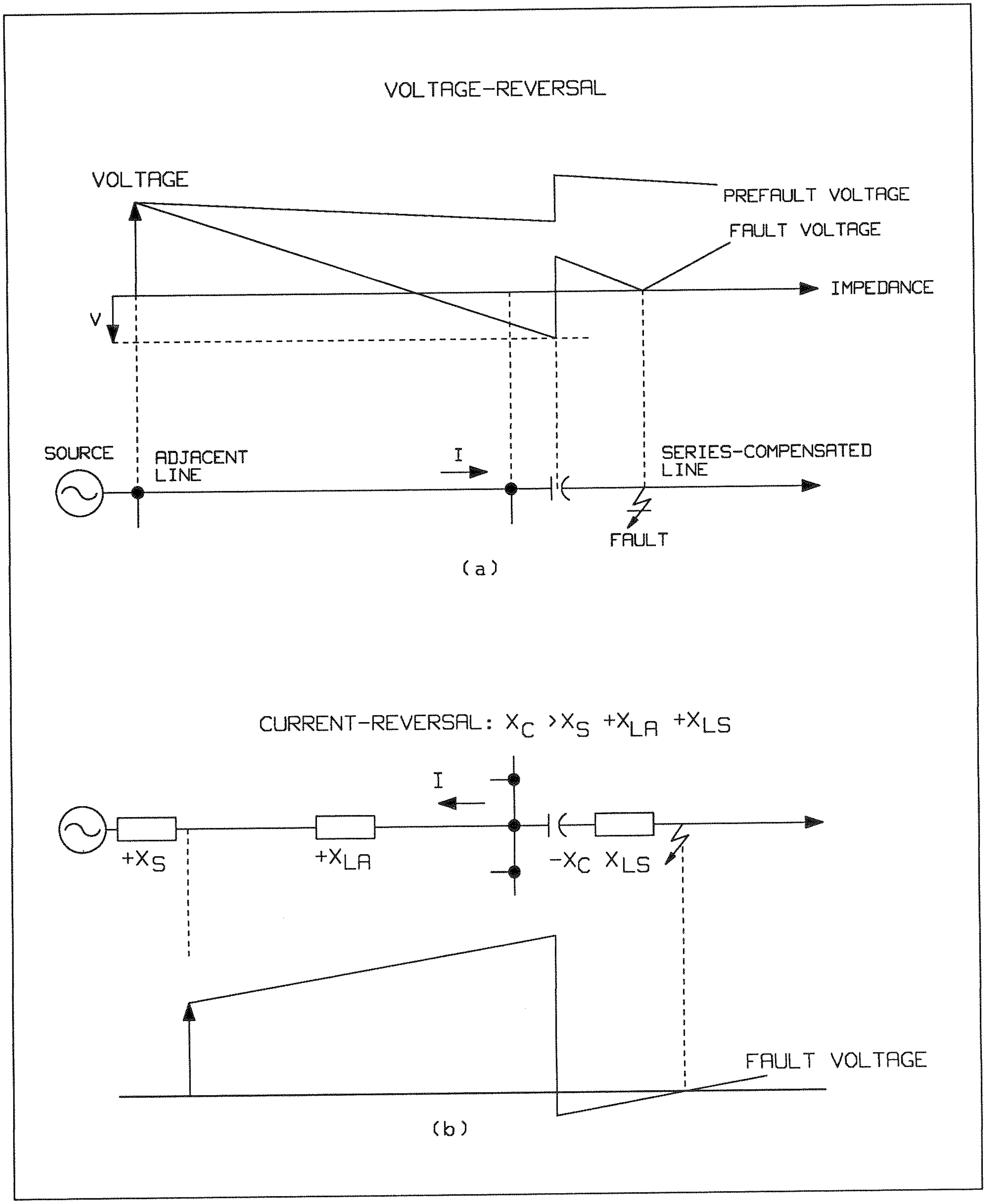


Figure 2. Apparent Impedance at 60 HZ under Fault Conditions.


VOLTAGE-REVERSAL

CURRENT-REVERSAL: $X_C > X_S + X_{LA} + X_{LS}$

Figure 3. *Voltage and Current Reversal*

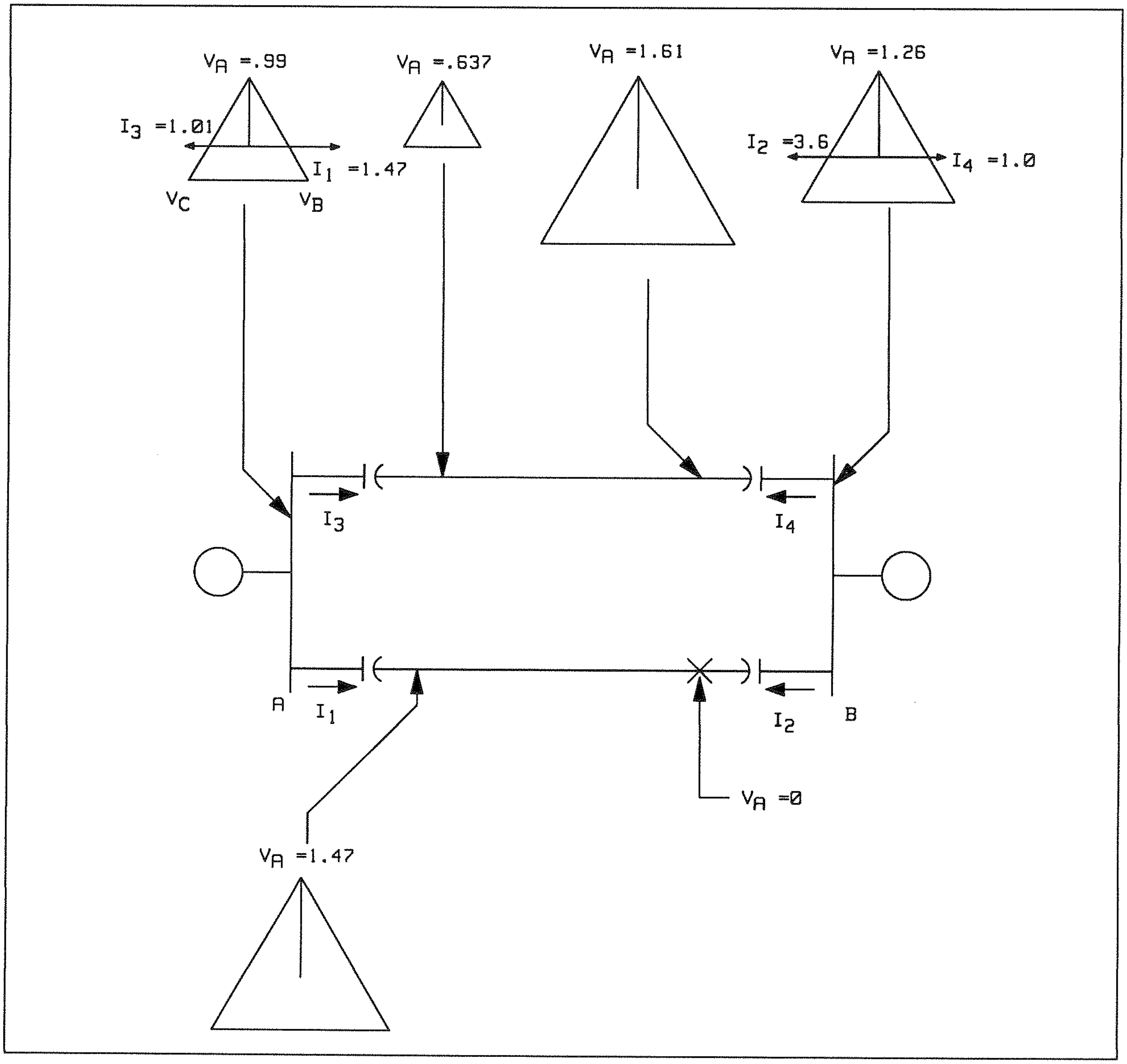


Figure 4. Typical Voltages and Currents for Fault at Capacitor-Line Junction ($X_S = 0.1$, $X_C = -0.35$, $X_L = 1.0$)

adjacent lines. This can result in "zero" voltage occurring on lines which are located far away from the series capacitor. The voltage can be zero only in a network with negligible resistances. In a real network the remaining voltage is so small that it can be regarded as zero.

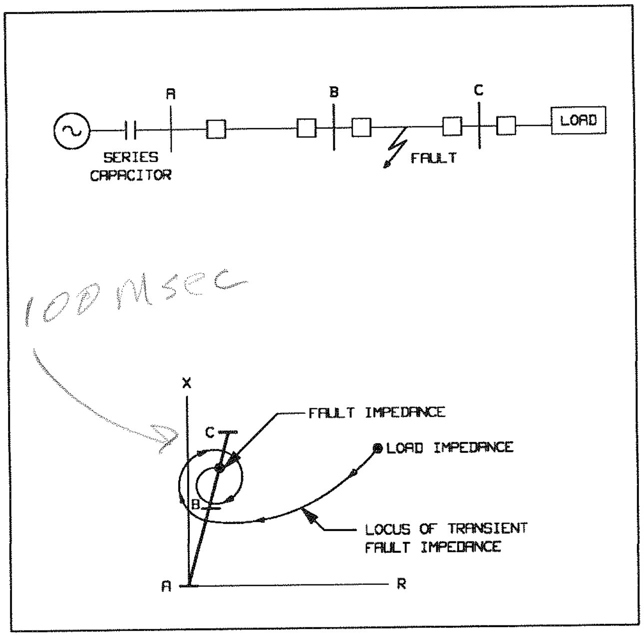
6. When a fault occurs on an uncompensated transmission line, the impedance presented to the relays swings instantaneously from that representing the load to that representing the fault condition. Because of a decaying low frequency transient component present in faults involving series-compensated lines, progress from the load point to the fault point on fault incidence may not be instantaneous. Instead, it may follow a logarithmic spiral as indicated in Figure 5. Large amounts of compensation can result in the fault taking as long as 100 ms to progress from the load to the fault point.

Distance Protection

Series compensation of a network will affect the distance protection on both the compensated line and adjacent lines connected to bussbars where a voltage reversal can occur. Generally, the most severe problems occur with the relaying associated with the adjacent line.

The following problem areas can be identified:

- Determination of direction to a fault
- Low frequency oscillation
- Transient caused by flashing of bridging gaps
- Transfer of capacitor reactance to resistance by metal oxide element bridging the capacitor
- Zone reach measurement
- False voltage "zeros" on adjacent healthy lines.



100 msec

Figure 5. Transient Fault Impedance

Distance protection will experience difficulties in determining the correct direction to a fault in a station where a voltage reversal can occur. Where direct polarization (polarization voltage from the faulty phase) is used the protection on both the faulty and healthy lines may see the fault to be in the improper direction. This false direction determination will take place with both mho relays and plain directional elements.

To overcome this and achieve correct directional measurement, polarization quantities from the healthy phases are utilized. Healthy phase quantities will not be reversed, and a correct directional measurement will be achieved for all unsymmetrical faults for an unlimited time.

Cross-polarized mho relays will under some fault conditions overtrip on adjacent lines because of the use of a single comparator for both the direction and reach measurement and therefore additional measuring criteria are required.

In the case of the three phase fault, where all phase voltages reverse, only memorizing of the prefault polarizing voltage can be used to achieve a correct directional determination. Normally in distance protection, the memory voltage is used only when the voltage is reduced to some percentage of the nominal voltage. This criteria cannot be used where a voltage reversal occurs. The use of the memory voltage must be controlled by general non-directional three phase fault criteria.

The time the memory voltage can be used must be limited to approximately 100 ms. Today, memory can be made very accurate but in the case of a three phase fault, the prefault condition should only be extrapolated for a limited time after the fault. The network is in a changing state and will run out-of-synchronism with the memory. Therefore, directional measurements have to be sealed-in after the time the memory becomes unreliable.

The low-frequency transient that occurs in a series-compensated system can be seen in the impedance plot as a transition from load impedance along a logarithmic spiral as shown in Figure 5. This transition can cause both over and under reach as well as a false direction decision. This problem is overcome with high pass filtering of the measuring quantities.

The transient caused by flashing of bridging gaps will jeopardize the security of the relaying system. Also, line-energizing transients are high-frequency in character and could cause some relays to operate. To avoid unwanted tripping, low pass filtering of the measuring quantities is necessary.

The problems above require that band-pass filtering be used on the measuring quantities. The requirement of bandpass filtering exists in all distance protection, but is much more pronounced in applications involving series-compensated networks to avoid unwanted operation.

With increased current through a capacitor bank and increased "conducting angle" of the parallel metal-oxide element, the capacitive reactance will start to diminish and the combination will have a resistive component as seen in Figure 1. When setting impedance relays on the compensated line, allowance for this apparent resistance is necessary to assure tripping at all fault current levels.

The measured impedance during a fault on the compensated line will change due to the negative reactance of the capacitor and the status of the gaps and metal oxide element in parallel with the capacitor. To overcome this change in impedances, a zone 1 impedance measurement must be shorter than the line with unabridged capacitor, and an overreaching zone must be longer than the uncompensated line. With this setting the permissive underreaching transfer trip system cannot be used. Of the distance-type schemes only a permissive overreaching system such as POTT or a blocking system may be used on series compensated lines.

The voltage reversal on the bus for a fault on a series compensated line can be seen as a false fault on adjacent lines. On these lines, the voltage is reversed at one of the terminals and the voltage is "zero" in one position on the line. An unwanted trip is avoided by using the proper polarization as previously described.

At the terminal remote from the bus where the voltage reverses, the voltage "zero" cannot be distinguished from a real fault. Therefore, independent zone 1 trip can generally not be used in such a location.

Directional Comparison Protection

This scheme consists of directional relays with limited or infinite reach. With measuring elements similar to distance relays, the directional comparison protection will have the same limitations as described above for distance protection. To overcome some of the limitations, negative and zero sequence directional relays are used for unsymmetrical faults, together with a directional relay of the impedance type for three-phase fault. Both negative and zero sequence relays polarized with their respective voltages will respond with the directional sense shown in Figure 6 for ground faults in approximately 15% of the line lengths near the capacitors in systems with parallel compensated lines. The directional comparison protection will thus fail to operate for these unsymmetrical faults and furthermore, this scheme has the same limitations as distance protection for three-phase faults.

The directional comparison type concept is also affected by the well-known problem of power reversal illustrated in Figure 7. Tripping at the right hand terminal near the fault, produces a reversal in the upper line. The power reversal is overcome by transient blocking logic, but this may introduce a delay in clearing an evolving fault which initially is external and then becomes internal. Transient blocking is also required for the permissive overreaching transfer-trip system. The performance of the directional-comparison scheme is relatively similar to the distance protection scheme but is lacking the backup function inherent in the distance protection scheme.

Directional Wave Protection

Directional wave protection is based upon the use of directional detectors which evaluate the sudden change in voltage and current caused by a fault. The directional discrimination is accomplished in 2-4 ms. During this very short measuring time, the voltage across the series capacitor bank will have changed very little. To change the capacitor voltage, energy must be forced into the bank. The inductances in the system will limit the amount of energy that can be transferred during the first few ms.

Since the capacitor bank voltage is not changed significantly during the time for directional measurement, the capacitor

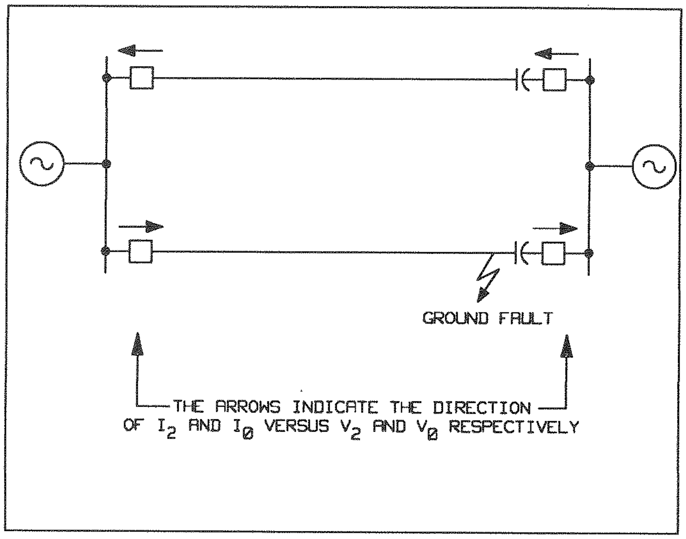


Figure 6. Negative and Zero-Sequence Directional Relays

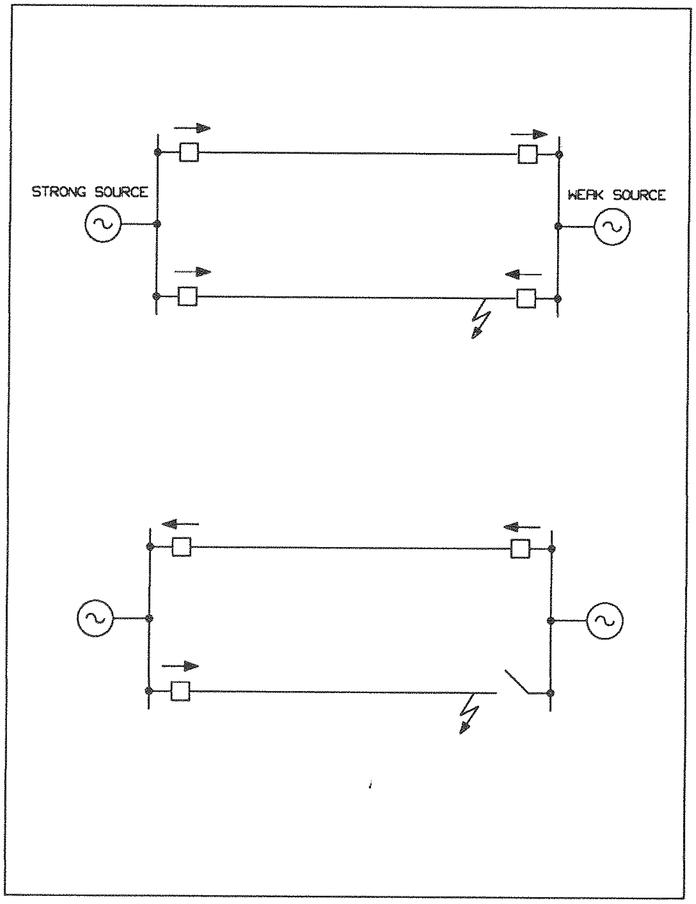


Figure 7. Directional-Reversal

will not influence the measurement. The directional measurement is used in a directional comparison cooperation scheme by linking the two line terminals via a single transmission channel. Directional wave protection will thus not be affected by the series-compensation, and can be used on compensated lines as well as adjacent lines which are affected by the compensation. The sensitivity is increased by weak-end-infeed echo and trip functions.

The bridging of a capacitor on a protected line will be seen by directional wave protection as a change similar to an in-line fault. The sensitivity will be set not to trip when the capacitor is bridged for an external fault. This sensitivity is sufficient for all phase-to-phase faults including three phase faults.

To increase the sensitivity to ground faults, an additional directional detector with higher sensitivity can be included. To avoid false tripping at bridging of the capacitor bank, an additional criterion is required. This criterion is a control that a zero sequence current must exist 20 or 40 ms after the operation of the directional wave detector.

A system block diagram is shown in Figure 8.

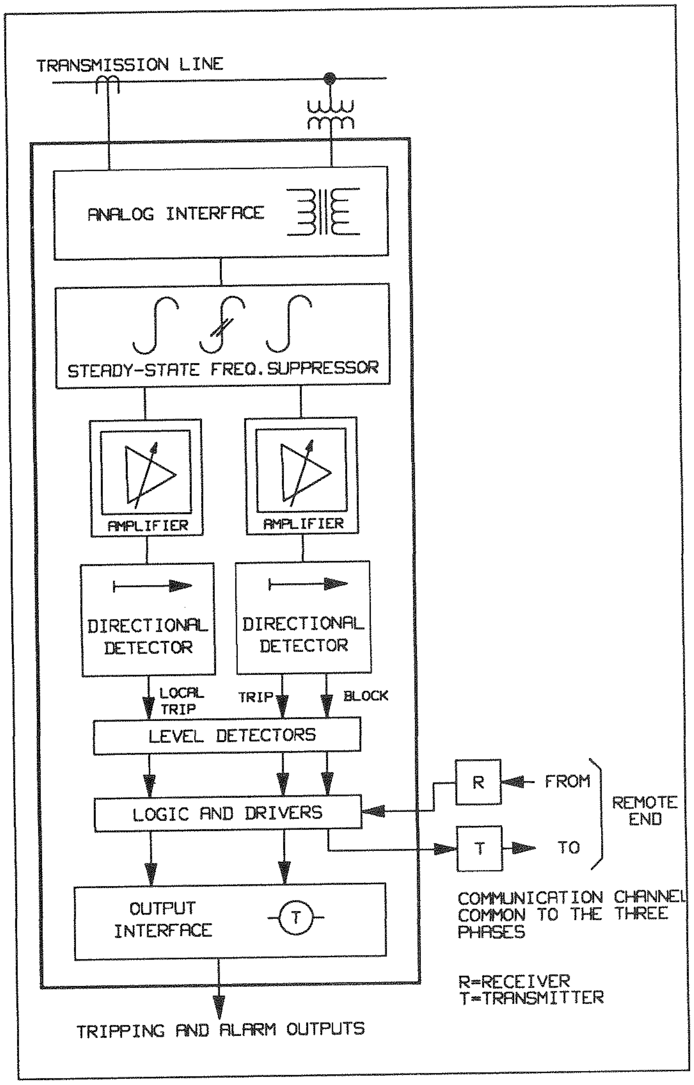


Figure 8. Directional Wave Protection Block Diagram

Phasor Differential

This system is similar to a phase-comparison system except for the fact that relative phase position of currents at the two ends of a transmission line is not the sole criterion used by this relay system for judging whether a fault is internal or external to the line. Rather, the actual phasor differential between the local and remote quantities, along with a summation restraint, is used to establish the need to trip or restrain.

One form of phasor differential, the LCB system, utilizes a single phase voltage that is developed at each transmission line terminal. This voltage is proportional to the symmetrical component content of the input currents. A different selectable weighting factor is used for each of the positive, negative, and zero sequence components. The resultant voltage is referred to as the filter output voltage.

Communications between the two ends of the transmission line is achieved in all of the conventional ways. This fundamental frequency voltage (50 or 60 hertz) that is developed is sampled by a pulse period modulator. This device creates a voltage having a frequency that is inversely proportional to the instantaneous magnitude of this voltage. The nominal frequency about which the variations are generated is 1700 hertz. A single voice band in each direction is adequate.

With the frequency of the communications signal being dependent on the instantaneous value of the symmetrical component filter output voltage, the receiving terminal is able to convert this readily into an analog voltage, accurately recreating the remote filter voltage. Each terminal then has access to its properly delayed local filter output voltage and the remote filter voltage. A simple comparison, accomplished in a manner similar to that for a generator differential application, is then made. The operating quantity that is used is the magnitude of the phasor sum of the two filter voltages. The restraint quantity is the sum of the magnitudes of the two.

This scheme is suitable for use on some lines equipped with series capacitors. Voltage is of no concern to this system. External faults produce no problems. Internal faults with outfeed that does not cause gap flashing are a problem. High resistance internal ground faults with large "through" load current may produce a problem. A simultaneous open and internal ground fault or a simultaneous external and internal fault may be troublesome. Unsymmetrical gap flashing or incomplete transpositions may cause 3-phase faults to go undetected, due to heavy zero-sequence weighting.

Phase-Comparison

The basic phase-comparison system is a scheme in which a single phase filter voltage is developed at each transmission line terminal that is dependent on the symmetrical component content of the phase currents. Communications equipment is keyed during the positive half cycle. Using the received signal, a comparison is then made to establish whether the filter voltages are approximately coincident as they would be for an internal fault or 180 degrees apart for an external fault or load condition.

Fundamentally this scheme has served the industry well, but it is subject to all of the problems listed for Phasor Differential plus the problem of light current crossover. Neither has inherent backup nor provision for single pole trip.

Offset Keying

The simplicity of the phase-comparison protective relaying system encourages its consideration for series compensated transmission line applications. With no voltage used for the basic relaying concept, all of the problems associated with voltage aberrations are eliminated. Any "through" phenomenon, being at rated frequency, low frequency or high frequency, create equal influences at each of the line terminals. Only the charging current of the line exists as a quantity with which we must reckon, to assure security. This is easily handled by the offset keying concept as will be seen later.

For internal faults, two circumstances that must be handled are 1) outfeed at one terminal and 2) large-through load-current with a high resistance internal ground fault.

Combining segregated phase comparison with offset-keying produces an excellent combination for single-phase trip, series-compensated line relaying. Segregated phase comparison systems compare the "in" and "out" currents for each phase at the two terminals of the transmission line, and do not use a 3-phase composite symmetrical component filter. The system becomes inherently phase selective and may be used to trip only the phases involved in a fault, irrespective of the number of phases, if desired.

It is oblivious to the usual difficulties encountered with faults involving more than one transmission line. Evolving faults produce no problem. Zero sequence mutual has no detrimental effect.

A sophisticated communications system is required if all of the pertinent information needed from the remote terminal for a trip decision at the local terminal is to be transmitted over a single voice channel. The MSPC system accomplishes this using a quadrature-amplitude-modulated system. One voice channel total (for 3-phase and 1-ground subsystem) is required in each direction, and the coded signal includes the information required for another function such as remote trip.

Figures 9 and 10 describe the offset keying concept applied in the MSPC segregated-phase-comparison system. An important characteristic of this system is that three distinct current levels are established; the channel (trip positive) keying level, the local positive and the local negative levels. The keying level is positive and set comfortably between the other two in magnitude with a margin to accommodate charging current. The channel is keyed to the trip positive state when instantaneous current is above a certain positive threshold, typically 1.675 amperes (2 amperes RMS for 3 ms key). Local positive is at a "one" state for instantaneous current more positive than a negative threshold value, typically 0.8376 amperes. Similarly, local negative is at a "one" state for instantaneous current more negative than a negative threshold value, typically 2.513.

For those power system conditions which produce outfeed (one terminal feeding current into the fault and the other terminal current 180 degrees out of phase with that) for a fault internal to the transmission line, the TP key level is set above the magnitude at the outfeed current location. Tripping occurs as

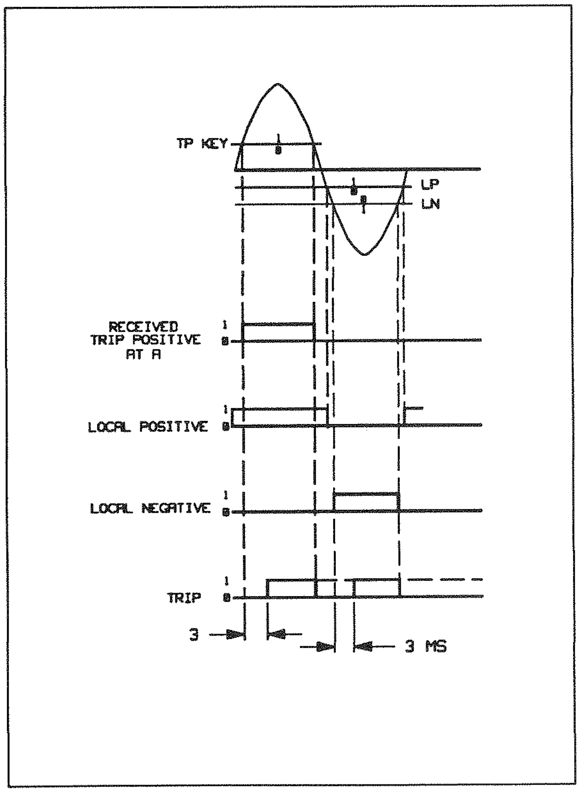


Figure 9. MSPC Waveforms
Internal Fault
Both Currents

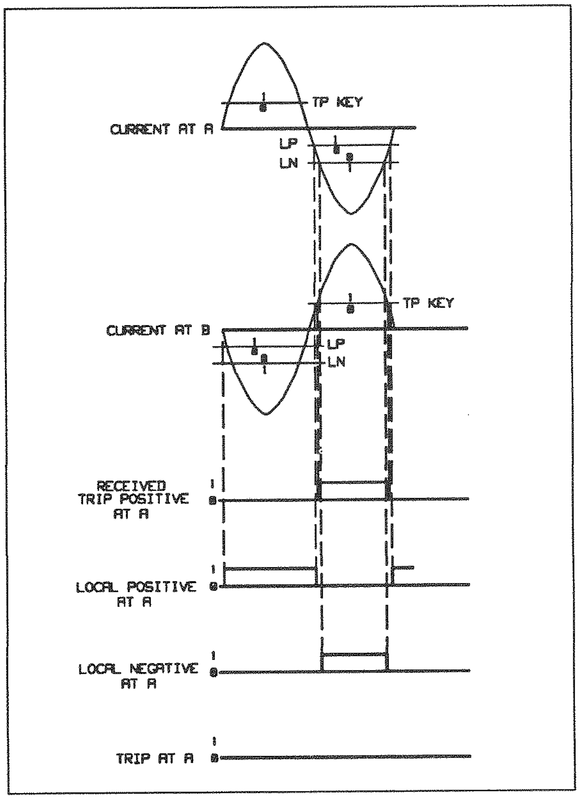


Figure 10. MSPC Waveforms
External Fault

a result of a large local negative value at the other terminal. All tripping clamps the transmitters to the trip positive state.

Previous implementations of this concept have utilized four frequency-shift voice channels in each direction and contained no distance backup. The MSPC system is a coded quadrature-amplitude-modulated system and requires only one voice band in each direction for the four subsystems (3 phase and 1 ground). Further, a two-zone time-delayed offset-distance, non-pilot backup system is incorporated as an inherent complementary function. Phase selection utilizes a patented $I_1 + I_2$ comparison scheme for optional backup single pole tripping. Dual blinder out-of-step tripping and blocking is also included.

All of the shortcomings of the fundamental frequency voltage dependent systems have been overcome by the MSPC system and exhaustive tests indicate that no new ones have been created.

Importance of Combinations

Historically, it has been demonstrated that any problem we can identify and repeat, we can find a solution for. Problems have a way of lingering, unidentified until the worst possible moment arrives. Sooner or later every protective relaying system displays a shortcoming. Some fault combination, some fault incidence angle, some set of system parameters, some pre-fault load condition, some phase impedance unbalance, some unsymmetrical gap flashing event, some switching condition, some off-normal frequency excursion, or some instrument transformer malfunction will cause a deficiency to appear. It may be a large one or a small one.

Using a second protective relaying system having a totally different measuring concept will invariably cover that rare exposed shortcoming of the first system. A second different system is recommended in any important transmission line application, particularly where a series capacitors and/or single-phase tripping is used. These produce very complex power systems, and they generate a host of challenging phenomenon.

Importance of Model Power System & EMTP Testing

A modern Model Power System is extremely expensive if it is to fulfill the needs for elaborate and accurate power system representation. What this large investment allows is very wide flexibility in parameters, refined control of fault application, reproducible power system phenomenon, wide variety of load conditions, extensive data acquisition and high resolution and clear plotting capability.

The Electromagnetic Transients Program (EMTP) adds to this important test facility, the ability to model a far more extensive system, to do so with uniformly distributed parameters if desired, to totally define the waveforms, and to eliminate undesired component effects. Provision for both types of tests must be incorporated in a manufacturers developmental facility. Each has its strengths and weaknesses.

The MPS is most likely to provide useful surprises in the behavior of protective relaying system. Being a real time system with real current transformers having an arbitrary residual flux level with real trip and reclose action, arbitrarily generated control power transients and realistic inequitable pole action of breakers testing occasionally leads to unexpected performance of the relays. However, all of this can be repeated on the MPS.

From the viewpoint of ease of generation of the next case, infinite ability to explore the fringe phenomenon, feasibility to examine intricacies on virtually a microscopic basis, the MPS has no equal. The immediate interaction between the MPS, the relaying system and the test engineer on a closed loop basis provides a synergism that is not possible in any other way.

The EMTP approach, on the other hand, allows a pre-established sequence of waveforms unaffected by ct (current transformer) resistance, unaltered by undesired ct and ccvt transient behavior. It is effective for users and small manufacturers with limited testing facilities who desire the assurance provided by the application of a fixed series of difficult tests.

A comparison of the programming requirements is useful. Other than the preliminary one-time programming for the control and data collection, none is required for the MPS. New cases can be set up in minutes by personnel with no programming knowledge. Each new case to be run on EMTP requires the attention of an experienced programmer.

Both facilities provide important capabilities not present in the other, and it is expected that both will continue to be used in the development of protective relays.

CONCLUSIONS

This paper has attempted to describe the difficulties associated with the relaying of a transmission line equipped with a series capacitor and has described various transmission line relayimg systems.

The segregated phase comparison system and the directional wave protection systems appear to offer the most straight-forward solution to this difficult relaying application.