A High-Speed Directional Comparison Protection for EHV Transmission Lines

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Introduction

This paper describes a new directional comparison relaying scheme which uses the instantaneous changes in the line currents and potentials caused by a fault. It provides complete high-speed protection for all fault types using a standard communication channel, back-up protection in case of channel failure, and separate sensitive ground fault elements. The directional comparison elements operate in either a permissive over-reaching or a blocking mode.

The salient features of this protection scheme are :

1) three high speed superimposed component directional elements for use in a blocking or permissive over-reaching transfer trip scheme,

2) six back-up distance elements for instantaneous or time delayed tripping (these are independent of the communication channel),

3) an element to cover trip-on-close conditions,

4) a phase selector which allows single phase tripping.

The operating time of such a relay is about:

Directional decision	**0.2 cycle**	**3.4 mSec**
Processing time		**2.0 mSec**
Contact output time		**2.0 mSec**

Total time = 7.4 mSec plus channel time.

Operating Principle

The directional detection elements use the changes in the voltages and currents at the relay location, which are induced by the fault. These changes are the quantities which are superimposed on the pre-fault values by the fault: for example the voltage after the fault has occurred is the sum of the prefault voltage and the superimposed component. The relationship between the superimposed components of voltage and current can best be understood by reference to Figure 1.

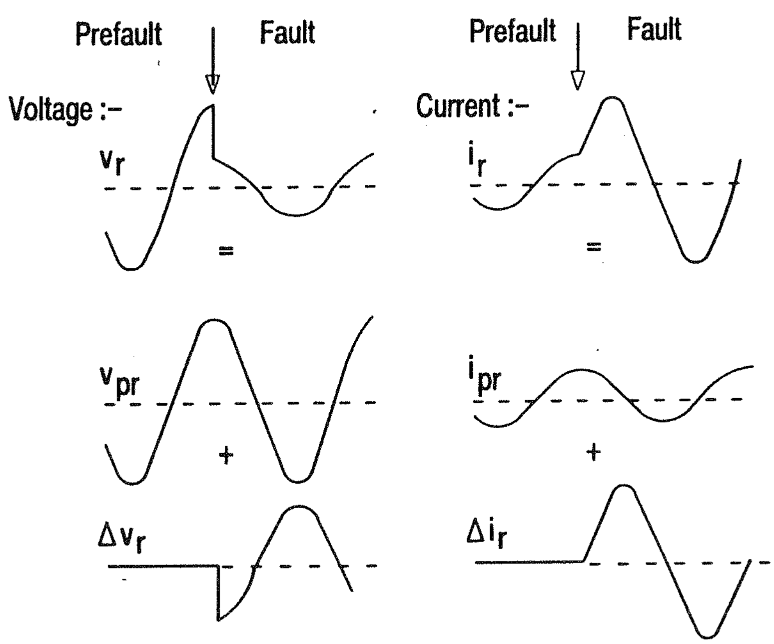


Figure 1
Illustration of the Superimposed Components

The fault voltage signal **vr** consists of the prefault voltage signal **vpr** plus the superimposed voltage signal **Δvr**. Similarly, the fault current signal **ir** consists of the unfaulted current signal **ipr** plus the superimposed current signal **Δir**.

$$vr = vpr + \Delta vr$$
$$ir = ipr + \Delta ir$$

The directional elements evaluate the direction to the fault by examining the phase angle between the superimposed voltage and the superimposed current. The superimposed voltage is phase shifted by an angle approximately equal to the angle of the source impedance. For solidly grounded EHV systems, the variation in the angle of the source impedance - whether dominated by overhead lines, cables or transformer feeders - is inductive and therefore is restricted to a small range of angles. For this reason, the phase shift is fixed at 78 degrees. This angle is close to the source angle of typical systems and, as will be seen later, is determined by the design of the digital filters. A definite relationship exists between the superimposed voltage and current signals. For a forward fault the superimposed current and the phase shifted superimposed voltage are of opposite polarity. For a reverse fault the superimposed current and the phase shifted superimposed voltage are of the same polarity. (Current flowing into the line is always considered as being positive.)

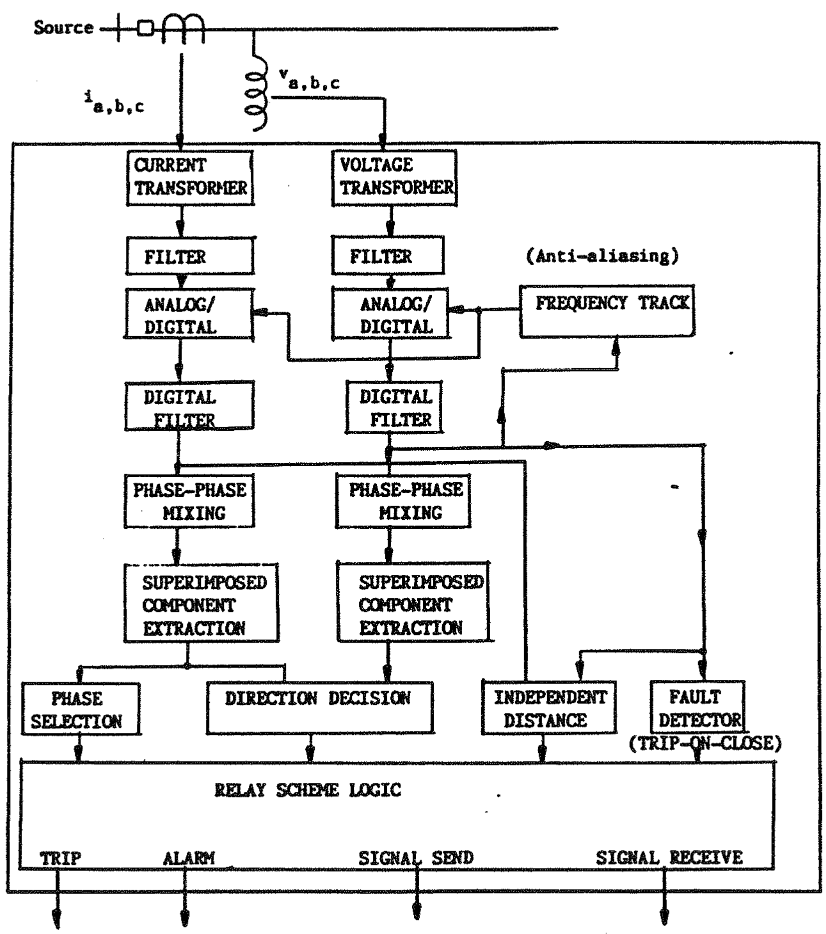


Figure 2 - Block diagram of the relay

Implementation of the Operating Principle

The directional comparison elements of the relay (shown in Fig. 2)consist of the following:

- **input voltage and current transformers**
- **anti-aliasing filters**
- **analogue to digital converter**
- **digital voltage and current filters**
- **superimposed component extraction filters**
- **a directional decision element**

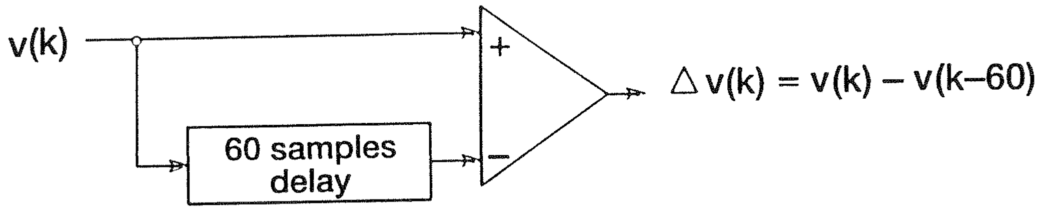
The analog input circuit transforms and isolates the input voltage and current, and provides anti-aliasing filtering. Sampling of the voltage and current signals is done at a rate of 60 samples per power system frequency cycle by a 12 bit analogue to digital converter. A frequency track algorithm adjusts the sampling rate in accordance with the power system frequency, the sampling rate is always 60 samples per cycle irrespective of the actual frequency. The voltage and current signals are then digitally filtered.

The current filter is designed to reject all frequencies higher than 500 Hz. The delay of this filter is 7 samples or 42 degrees. The voltage filter is designed to phase delay the voltage signal with respect to the filtered current signal, by the source angle. The phase delay of the voltage filter is 20 samples or 120 degrees. The difference is therefore 120° - 42° = 78° and this represents a typical source impedance angle. This filter rejects frequencies higher than 180 Hz.

The direction to the fault is determined using the superimposed phase to phase voltage and current signals. The use of phase to phase signal reduces the effect of mutual coupling for a fault on the parallel circuit of a double circuit line.

Superimposed Component Filter

The output of the superimposed component filter is the difference between pre-fault and the fault signals for 60 samples after the occurrence of the fault. After this 60 sample period, the output of the filter is the difference between two samples of the fault signal, exactly 60 samples, or one cycle apart. This is shown in Figure 3.



- a–b, b–c, c–a "phase – phase" superimposed voltage and current signals are derived
- The frequency track adjusts the sample rate to ensure :– 60 samples = one power frequency cycle
- The output of the superimposed "filter" is the difference between the post–fault and pre–fault signal for one cycle after the fault occurrence

Figure 3
Superimposed Component Extraction

The angle between the superimposed current and the phase shifted superimposed voltage is measured by mixing the signals in accordance with the equation:

$$\mathbf{(S2\text{-}S1) = [S2] - [S1]}$$

where $S2 = \Delta vr\angle{-78°} - \Delta ir$ **and** $S1 = \Delta vr\angle{-78°} + \Delta ir$

For a forward fault, since the magnitude of S2 is greater than the magnitude of S1, the function (S2-S1) is positive. Conversely, for a reverse fault, since the magnitude of S1 is greater than the magnitude of S2, the function (S2-S1) is negative.

The operational range of the comparator is ±90 degrees so with the −78 degrees phase shift in the voltage the overall operating angle is +12 degrees to -168 degrees for Δir with respect to Δvr.

The sensitivity of the directional elements is limited so that a current change of greater than 20% of rated current and a voltage change of greater than the voltage setting are needed for faults in the forward direction. The voltage setting is user adjustable within the range 1V-60V.

The superimposed directional elements are designed to be more sensitive to reverse faults than for forward faults. They will detect reverse faults that result in a current change of greater than 14% rated current and a voltage change of greater than 70% of the voltage setting.

Direction Decision Counter

Security dictates that the values from one measurement alone must not be used as the criterion for making the directional decision: a counter and threshold detector are thus incorporated. For every measurement where the signal comparison is positive (a forward fault) and this signal exceeds a threshold level, the counter is incremented. For every measurement where the signal comparison is negative (a reverse fault) and the threshold level is exceeded, the counter is decremented.

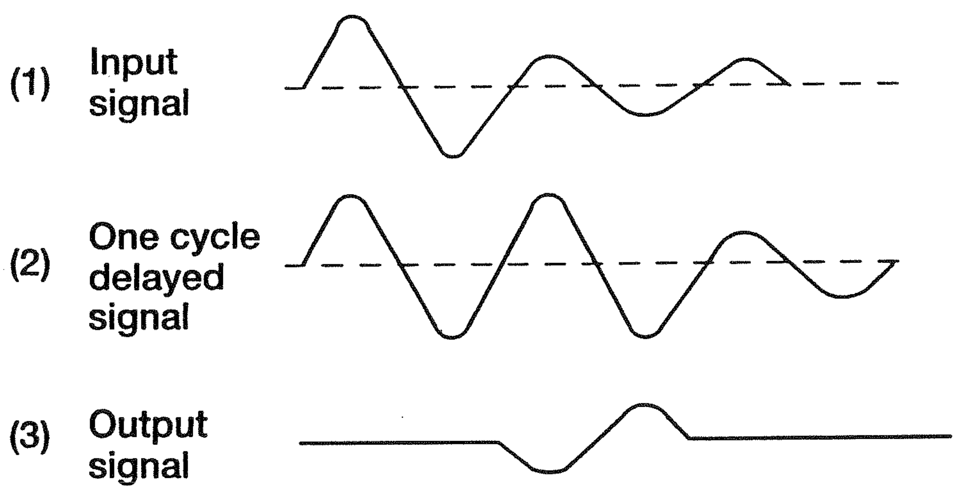
If the counter reaches +3 or -3 the appropriate (A-B), (B-C), (C-A) forward or reverse directional flag is activated. For example, for a phase B - C fault, all three superimposed component detectors will operate. A forward decision is made when any two forward flags are set. A reverse decision is made when one reverse flag and less than two forward flags are active.

The reason for biasing the decision towards the reverse direction is to ensure security against false tripping, this is of particular importance on series compensated lines.

The maximum allowable decision count is +8 for a forward fault and -8 for a reverse fault. These limits are imposed to ensure the relay can change its decision from reverse to forward or vice-versa without a long delay. This feature is required for cross-country or inter-circuit faults.

Relay Operation

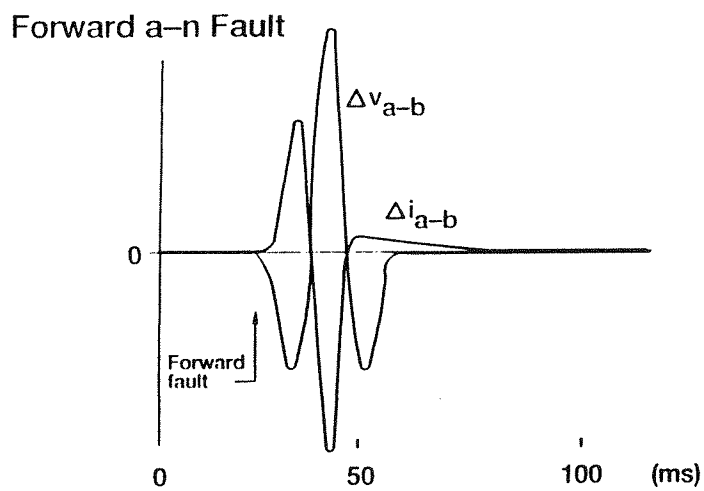
Figure 4 shows the relationship between the input and output of the extraction filter. The output is the difference between the pre-fault and fault signal for a period of one cycle after fault inception. Prior to fault inception and also after this one cycle period the output is ideally zero.



$$(3) = (1) - (2)$$

Figure 4
The relationship Between the Input and Output Signals of the Extraction Filter

Figure 5 shows the (A-B) superimposed voltage and current signals for a forward phase A to ground fault occurring with a point-on-wave (POW) of 0 degrees. The extraction filters completely reject the power frequency components in the voltage and current signals until the time of the fault. After fault inception, these filters reproduce the power frequency superimposed current and voltage signals for 16 ms and 24 ms respectively. This period corresponds to the one cycle extraction filter delay plus the delay associated with the voltage and current filters. After this period the extraction filters reject the post-fault power frequency components.



Fault at POW = 0^o

$Z_S = 4.0\angle 80^o\Omega$, $Z_L = 4.0\angle 80^o\Omega$.

Figure 5.
Rejection of Power Frequency Components by the Extraction Filter

Figures 6 and 7 show the (A-B) superimposed (S2-S1) signal and the corresponding (A-B) decision counter.

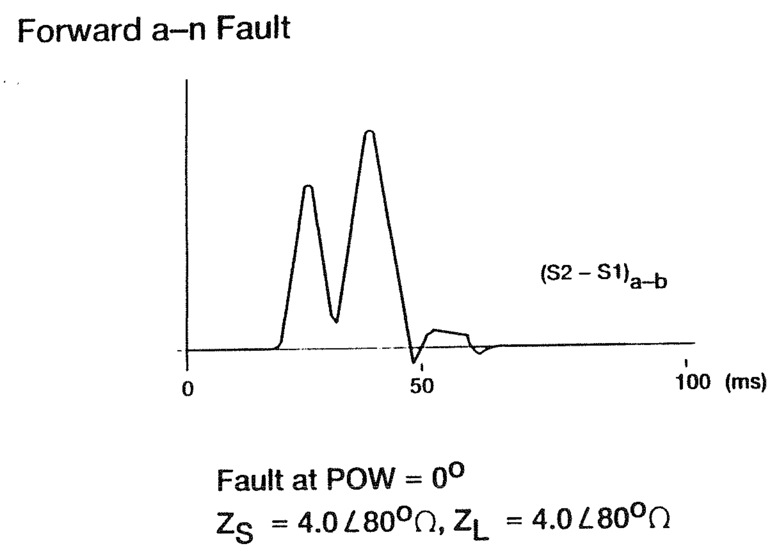


Figure 6
(S2 - S1) A-B Signal for a Phase A to Ground Forward Fault

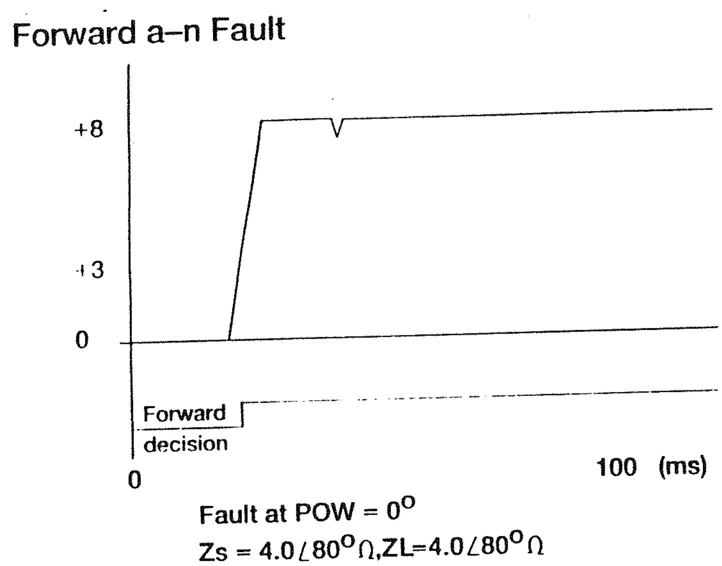


Figure 7
Counter Output for Figure 6

In Figure 6, the signal is positive for 25 ms after fault inception. For each sample that exceeds the forward threshold the output decision counter is incremented, as shown in Fig. 7. When the counter reaches +3 the (A-B) forward flag is activated. The counter continues to be incremented until the count limit (+8) is reached.

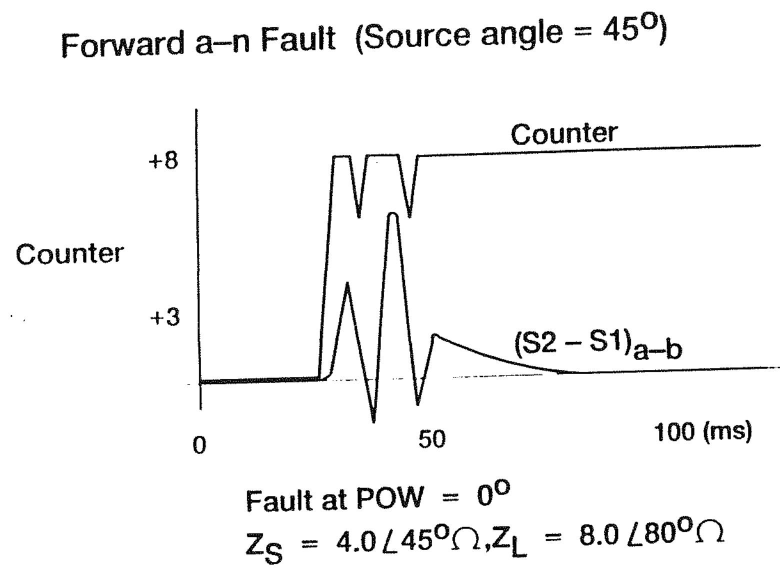


Figure 8
Signal and Decision Counter
Output for a 45° Source Angle

Figure 8 shows the (A-B) superimposed (S2-S1) signal and the corresponding (A-B) decision counter for a fault on a transmission line with a source/line impedance ratio of 2. The phase angle of the source impedance is 45 degrees and the phase angle of the line impedance is 80 degrees. The effect of operating the relay on a system with a source angle substantially different from the replica angle (78 degrees) is negligible.

Figure 9 shows the (A-B) superimposed (S2-S1) signal and the corresponding (A-B) decision counter when the phase angle of the source impedance is 0 degrees. Again the effect is negligible.

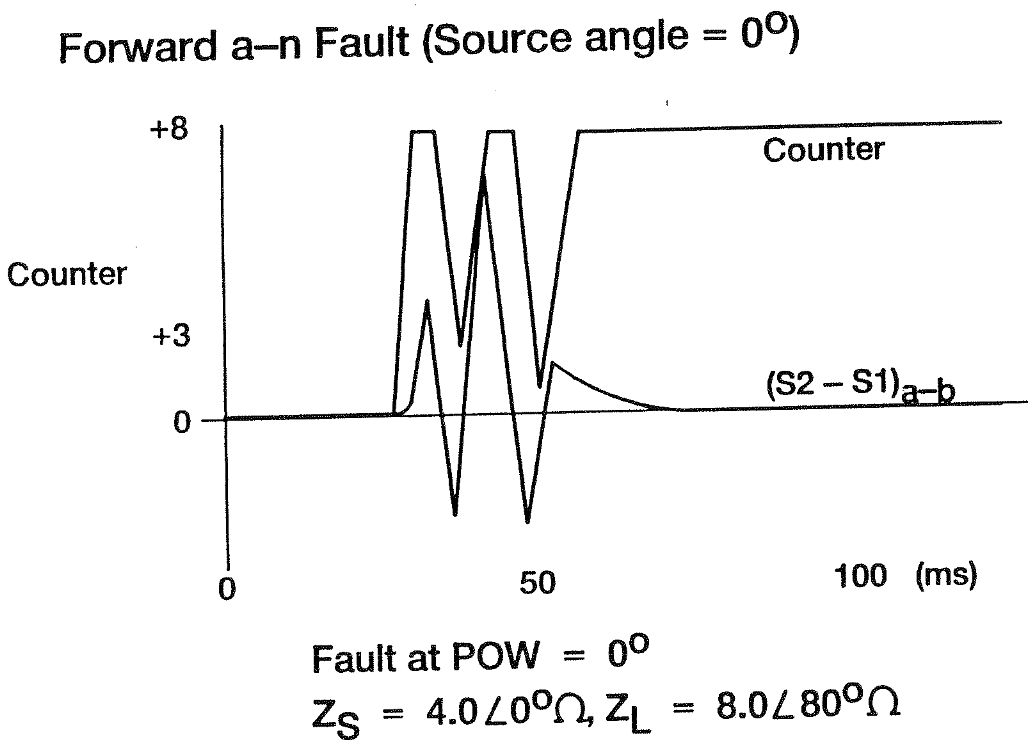


Figure 9
Signal and Decision Counter
Output for a 0° Source Angle

Phase Selection

The superimposed current signals are processed by the phase selector in order to determine the phase(s) involved in the fault. If an internal single phase fault occurs and if a single phase tripping scheme has been selected, the phase selector is used to direct the trip command to the appropriate phase of the breaker.

To evaluate the faulted phase(s), the phase selector processes the three superimposed phase to phase current signals. A single phase fault is detected if only two of the signals exceed a threshold: the faulted phase is the phase involved in the two active signals. For example, active (A-B) and (C-A) signals and an inactive (B-C) signal selects an A-ground fault. A multi-phase fault is detected if all three signals exceed a threshold. The threshold is chosen to ensure the phase selector is more sensitive than the directional elements, thus all faults that can be detected by the relay are correctly phase selected.

If the phase selector detects a multi-phase fault, i.e. all three superimposed phase to phase current signals are active, then the channel independent distance protection or the fault detector is used to determine which phases are involved in the fault. This also initiates the correct targeting and storage of the fault record.

Channel Independent Back-up Protection

The relay incorporates a protection option which is independent of the signalling channel. This provides back-up protection in the event of signalling channel failure. The channel independent option is implemented using one zone of distance protection. This zone can provide an under-reaching instantaneous protection that can be used to protect the line for close-in internal faults, or, the zone can be time delayed and set to over-reach the remote line end, thus providing back-up protection for the entire line.

The under-reaching distance zone is implemented using six memory polarized mho distance elements (A,B,C, A-B, B-C, C-A). The zone provides instantaneous fault clearance for all faults within the (zone 1) operating characteristics of the distance elements. To improve directional stability, the distance trip decision is supervised by the forward superimposed directional decision. The latter is insensitive to the effects of heavy circuit loading, ccvt transients and ct saturation.

The over-reaching distance zone is implemented using six memory polarized mho distance elements. The zone provides time delayed fault clearance for all faults lying within the (zone 2) operating characteristics of the distance elements.

Each distance element provides a mho characteristic operating zone, using a digital version of a memory polarized amplitude comparator. The comparator detects the fault as within its operating zone when the magnitude of the operate signal, IZ is greater than the magnitude of the restraint signal V-IZ.

To improve operating stability a decision counter is applied to the amplitude comparison. The counter is incremented if [IZ] > [V-IZ], i.e. the fault sample is in-zone. A counter is decremented if [IZ] < [V-IZ], i.e. the fault sample is out of zone. When the counter reaches +4 the fault is considered to be within the protected zone and the relay then initiates breaker tripping if the super-imposed directional decision is forward. The in-zone decision is maintained until the counter is decremented to zero.

Fault Detector

The function of the fault detector is to control the sensitivity of the superimposed directional elements during evolving and cross-country faults and to provide instantaneous protection of the entire line during manual and auto-reclosure.

The fault detector consists of memory polarized mho distance elements set to over-reach the remote end of the line.

The relay must protect the line for a fault evolving from an external to an internal fault. The superimposed directional protection will detect and inhibit tripping on the initial external fault, but if the fault evolves to an internal fault on the same phase the second voltage change may not exceed the voltage setting, consequently the protection would fail to clear the internal fault.

A possible solution to the problem of evolving faults would be to select the voltage setting at the minimum value of 1V. However, this means that for extremely remote system disturbances the relay at one end would be activated for a reverse decision while the relay at the other end would be activated for a forward decision. This would incur the risk of misoperation in a blocking scheme if the signalling channel were to fail.

The method used in this relay, to ensure adequate protection for evolving faults while restricting the operating range, is to increase the sensitivity of the directional protection once an initial fault has been detected. The directional decision is supervised by the directional fault detector. The fault detector consists of six forward looking and six reverse looking, memory polarized mho, over-reaching distance elements. The reverse looking reach is 20% greater than the forward looking reach.

Switch On To Fault Detection

The switch-onto-fault protection provides instantaneous tripping of the circuit breaker during manual or auto-reclosure onto a fault.

If a dead pole is detected (no voltage or current) the superimposed directional elements associated with the de-energized phase are disabled and the switch-onto-fault protection is enabled.

The switch-onto-fault protection detects all faults, except close-up 3 phase faults and high resistance faults. It uses a forward looking, sound phase polarized mho, fault detector. Close-up 3 phase faults are detected using under-voltage/over-current level detectors. High resistance faults are detected by directional ground fault protection.

Other Operating Conditions

The relay operates correctly under all of the following conditions:

High resistance faults.

The fault resistance coverage is significantly greater than that achieved by a distance relay. The ohmic value depends on the system being protected and the settings applied to the directional elements.

Evolving faults.

The relay operates correctly for a fault that evolves from a phase to ground fault to a multi-phase fault. For example, if the fault evolves from A - ground to A - B -ground, the protection initiates tripping on the A - phase and then converts the trip to three phase.

Cross-country and inter-circuit faults.

The directional elements are capable of changing their decision from reverse to forward. Consequently, if an internal fault occurs immediately after an external fault, the relay that blocked scheme operation, due to its reverse decision, now changes its decision to forward and the protection is allowed to trip the breaker.

Power-swings.

The superimposed currents and voltages produced by a power swing are generally too small to cause operation of the directional elements. However, a power swing blocking algorithm is provided to prevent operation of the directional elements during pole slipping or severe power swings.

Heavy circuit loading

Since the directional elements operate using the change in the voltage and current signals, the protection is able to withstand heavy circuit loading without the load encroachment problems of distance protection. The channel independent protection is also immune to load encroachment since its distance zone is supervised by a forward directional decision.

CT saturation

The directional elements are insensitive to the distortion caused by ct saturation since they operate before the onset of saturation and only require information about the polarity and phase of the current signal and not its true value.

CCVT transients

The directional elements are immune to ccvt transients. A ccvt transient occurs when the voltage collapses to a low value; hence, the power system voltage change is substantially larger than the ccvt transient.

High frequency travelling wave distortion.

The relay includes voltage and current filters designed to severely attenuate high frequency components. This ensures stable operation in the presence of distorted waveforms.

Summary

This directional comparison protection provides complete phase and ground fault protection for all types of EHV and UHV transmission lines. This includes series compensated lines, shunt compensated lines, cables and transformer feeders.

Since the operating principle is substantially different from distance protection, it is an ideal complement to distance protection when two independent protection systems are required.