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Current Differential and Phase Comparison Relaying Compared with Pilot Distance Schemes

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Presented to

25th Annual Western Protective Relay Conference
October 13-15, 1998
Spokane, Washington

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by W.A. Elmore

INTRODUCTION

Current comparison and distance pilot schemes are, in most cases equally applicable to transmission line protection, but each type has its distinctive nuances that make it more suitable for particular applications. It is expected that the reader will be familiar with the basic protective relaying schemes referred to here, but it is felt that some brief description is in order.

This paper attempts to describe the qualities of each of these systems and to point out where they excel.

DESCRIPTION OF RELAYING SYSTEMS

Current Differential

Current differential relaying began as a set of relays at each terminal of a transmission line that were interconnected by pilot wires. By approximately 1938, a practical and economical version of this concept had evolved. The modern version of this concept closely approximates a pure differential scheme, obtaining its "operating" quantity from the phasor sum of weighted local and remote currents at the two ends of the transmission line and its "restraint" quantity from the sum of the absolute values of these weighted currents.

To allow a single pair of pilot wires or a duo-directional tone or fiber optic channel to be used for the interchange of information from one transmission time terminal to the other, the "local" and "remote" quantities are single phase voltages that are generated by using the "A" phase weighted positive sequence plus weighted negative sequence plus weighted zero sequence current at each terminal.

Equation 1 describes this voltage.

$$V_F = C_1 I_{A1} + C_2 I_{A2} + C_0 I_{A0} \qquad (1)$$

For external faults, these V_F values generated at each end of the transmission line are essentially equal in magnitude, but are opposite in sign. This produces a near zero (phasor sum) operating quantity and, for the modern versions (LCB-II or REL356), a substantial (sum of the absolute values) restraint quantity providing the desired security.

For internal faults, the V_F values may have any magnitude, depending on the nature of the contributions of fault currents from the two terminals, but the phasor sum will be proportional to the magnitude of the fault current, providing an operating voltage. The restraint again is the sum of the absolute values of the local and remote V_F quantities. Identical operating and restraining voltages are produced at both terminals at all times. For faults having current magnitudes in excess of the relaying sensitivity, the relays at both ends of the line will trip simultaneously. A simple representation of this type system is shown in Figure 1.

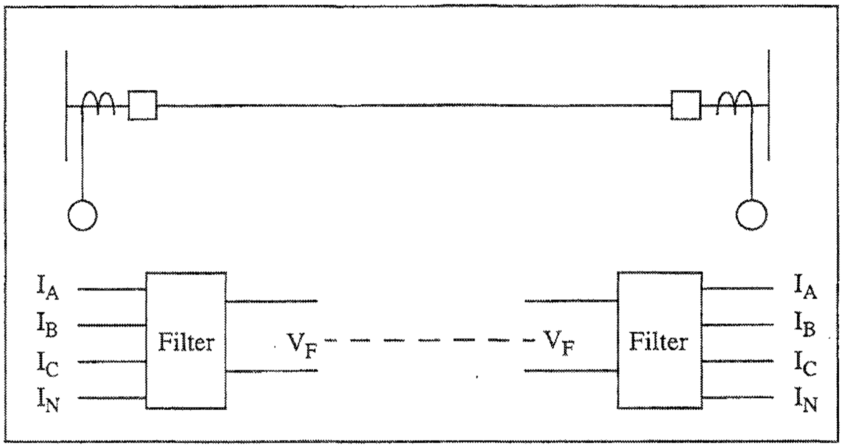

Figure 1. Basic Current Differential Scheme

Phase Comparison

The early versions of this scheme used a filter output voltage that was identical to that described in Equation 1. True "phase comparison" involves the appraisal of the interval of coincidence of the positive half cycles of these local and remote quantities and, in some relaying systems, the interval of coincidence of the negative half cycles also. Originally "on-off" power line carrier was used, allowing tripping for only the "off" half cycle (because the fault itself, for an internal fault, could cause the power-line-carrier signal to be severely attenuated).

Frequency shift power-line carrier and the "Unblock" concept allowed tripping on both half cycles of the filter output voltage. Frequency shift tones (on microwave or pilot wires) also allowed this without the need for "Unblock" control. The obvious benefit, of course, of being able to trip on each half cycle is that the range of trip times is narrowed by cutting 8 ms off of the maximum trip time while leaving the minimum trip time unaltered. This relaying system is, then, less affected by fault-incident angle.

With the advent of more efficient communications concepts, it has become possible with modern relaying to depart from the concept of symmetrical component composite filters and to accommodate phase comparison on the basis of individual phase current relationships at the two ends of the transmission line (Figure 2). Thus "phase A" current into the line at one end is compared to "phase A" current out of the line at the other end. Any difference which exists is fault current (excluding the minor effect of distributed capacitance). Similar comparisons are made for the other two phase currents and for zero sequence current. Modern phase comparison systems also contain stepped distance backup relaying which becomes operative if the channel should experience trouble.

Distance Pilot

Figure 3 shows the fundamental distance pilot scheme.

All of the "directional comparison" schemes (blocking, unblocking, overreaching transfer trip) utilize distance relays for the phase directional function. The ground directional function may be accomplished with a ground distance relay or a directional overcurrent relay (polarized in one of several different ways).

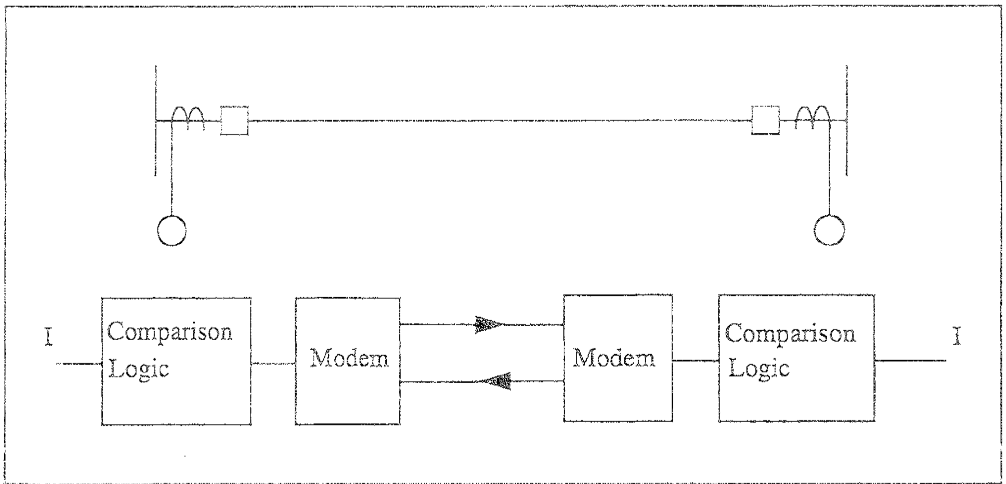

Figure 2. Example of Basic Phase Comparison Scheme

Directional comparison blocking schemes necessarily require a "carrier-start" function to operate for all external faults that the overreaching tripping relays reach. This may be a "reverse-set" phase or ground distance relay but must be an overcurrent (or rarely a directional overcurrent) relay when a directional ground overcurrent tripping relay is used. The need for coordinated sensitivity dictates this. Microprocessor relays have given us a powerful tool for carrier-start in the form of a $\Delta V/\Delta I$ function. It compares a sample of voltage (or current) with that taken 8 samples earlier (for an 8 sample per cycle device) identifying the occurrence of a "change" very quickly and sensitively, providing, where used, a very fast "carrier-start."

Directional comparison unblocking and POTT (permissive overreaching transfer-trip) relaying systems utilize continuous blocking in the form of a guard signal on the channel. This is shifted to the trip frequency by the operation of the phase and/or ground trip relay. Tripping of the circuit breakers at each terminal is accomplished by the operation of the trip relay simultaneous with receipt of the channel trip frequency. Where power-line-carrier is used, its dependability is augmented by providing a short trip window (150 ms) following loss of channel during which the trip relay may produce tripping.

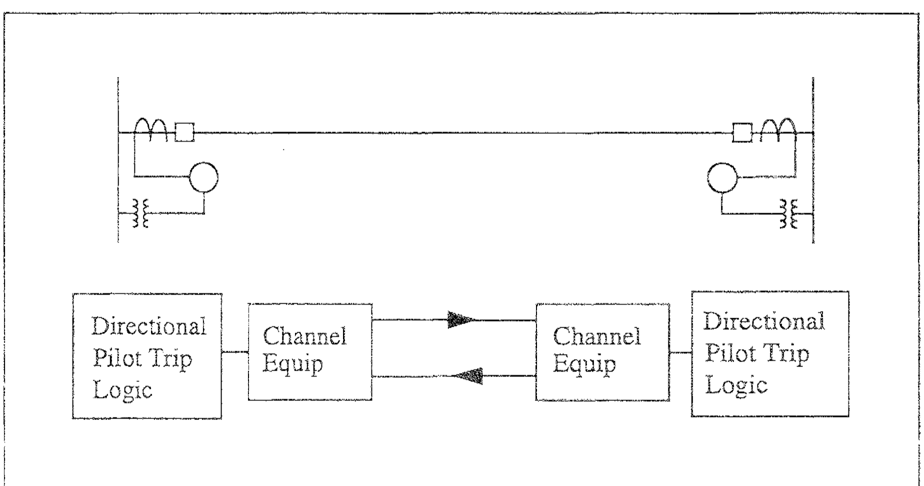

Figure 3. Basic Distance Pilot Scheme

Underreaching transfer trip schemes are also "pilot distance" schemes but not "directional comparison" schemes. They, necessarily use only ground distance relays (and, of course, phase distance) to key the channel trip because of the need for a distinct cutoff in their reach.

PROBLEM AREAS

Many power system phenomenon produce detrimental effects on some relaying systems, but not on others. This section describes some of these, and points out how they may influence the choice of one pilot relaying system over another.

A. Zero Sequence Mutual

Induced zero sequence voltage in one transmission line, resulting from zero sequence current in another (and the mutual impedance between the two) seldom has any beneficial effects. Figure 4 shows that the induced voltage may be in either direction, depending on the relative directions of current in the protected line and in the adjacent line.

Effect on Current Differential Relaying

Current magnitude is influenced by mutual, but internal faults appear to be internal and external faults appear to be external, irrespective of the extent of a mutually induced voltage. A ground fault on an adjacent circuit will cause zero sequence current to flow. All of the attributes of external faults are present and proper restraining takes place.

Effect on Phase Comparison Relaying

Phase comparison relaying is not affected by zero sequence mutual for the same reasons as for current differential. With zero sequence mutual, internal faults appear to be internal and external faults appear to be external – always.

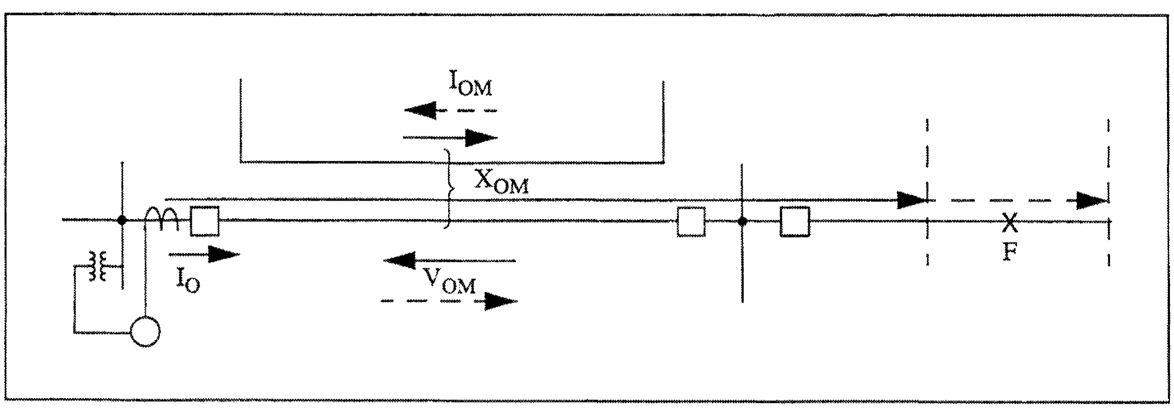

Figure 4. Pilot Distance Reach Variation caused by Zero-Sequence Mutual

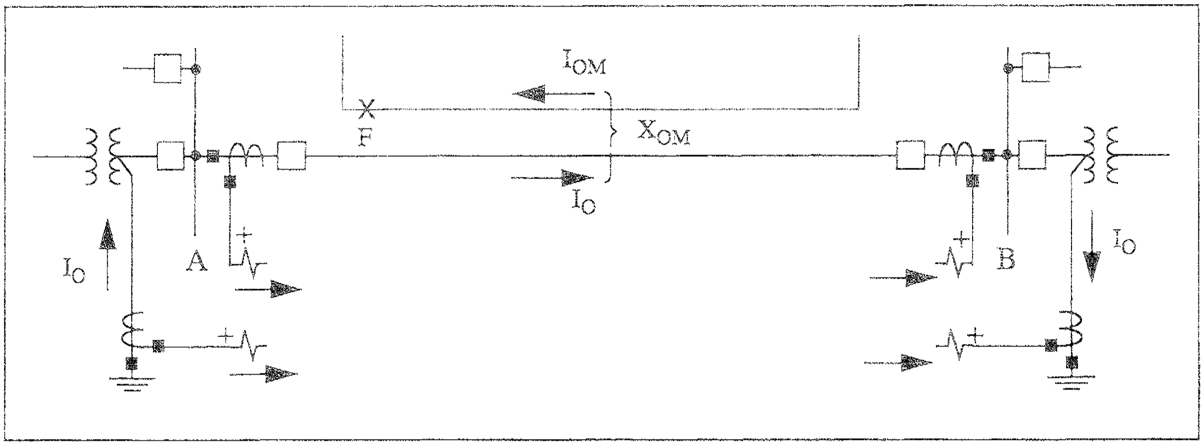

Figure 5. Directional Comparison Ground False Trip Caused by Zero Sequence Mutual

Effect on Pilot Distance Relaying

As Figure 4 portrays, zero sequence mutual can cause ground distance relays to underreach or overreach depending on the direction of the zero sequence current in the adjacent circuit.

Figure 5 shows a much more devastating phenomenon that results from a ground fault on an adjacent transmission line. The zero sequence voltage induced in the protected line A-B by zero sequence current in the adjacent line causes zero sequence current to flow through the line. This causes zero sequence current (or voltage) polarized directional relays protecting line A-B to operate. Unfortunately they operate at both transmission line terminals and for as long as the fault persists. False tripping results. Negative sequence directional units are immune from this.

B. Current Transformer Saturation

Adequate current transformers are vital in all pilot applications because of the need for security for all external faults. To design a relaying system to trip at high speed for all internal faults is a comparatively simple task. To equip it with the ability to refrain from tripping for all circumstances other than an internal fault poses a real challenge.

Current transformers experience errors in magnitude and phase angle. The most serious errors are those attributable to severe saturation of the core of the ct. It is felt that a review of this phenomenon as it relates to the behavior of modern solid state and microprocessor relays would be useful.

The simplest means by which the effects of saturation can be demonstrated is through the use of Figure 6. This represents the waveform of current that would be delivered to a relay while experiencing saturation at time T_S on each subsequent half cycle. No effect of dc offset in the primary current is considered in this Figure. After T_S and until the next zero crossing, zero current is assumed to be delivered by the current transformer to the relay. This is referred to as "symmetrical saturation". The process repeats each half cycle.

It is pertinent to examine the fundamental (60 hertz) content of this distorted waveform. Using Fourier analysis, the curve of Figure 7 was developed. It shows that symmetrical saturation occurring substan-

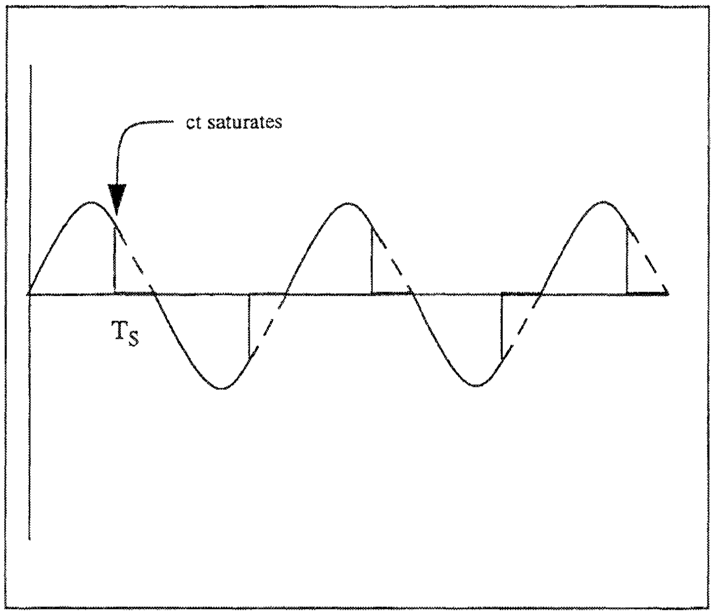

Figure 6. Ct Output During Symmetrical Saturation

tially after the peak does not produce extreme reduction of the fundamental (60 hertz) component.

Another extremely important influence in protective relaying is the current transformer asymmetrical saturation that may occur as a result of the dc component in the fault current. For internal faults the system should be designed in such a way that tripping is sealed before ct saturation occurs. This is related to V_K/IRT with V_K being the ct knee voltage, I the maximum symmetrical secondary current in amperes RMS, R the total secondary loop resistance in ohms and T the dc time constant of the primary in cycles (60 L/R). Protective Relaying, Theory and Applications Volume I (ABB/Marcel Dekker) chapter 5, Figure 5-11 describes this in detail. For external faults, assurance must be obtained that similar behavior will occur by the ct's at the two line terminals (good or bad) or that the nature of the relaying system will accommodate the maximum differences that can occur. For an external fault the ct's encounter essentially the same current, the same dc time constant and, having the same ratio, will behave similarly if their burdens and remanent flux are similar.

The waveform of Figure 8c was examined to determine the influence that a Fourier filter would have on sensing by a protective relay. No saturation is present and the waveform is considered to be delivered to

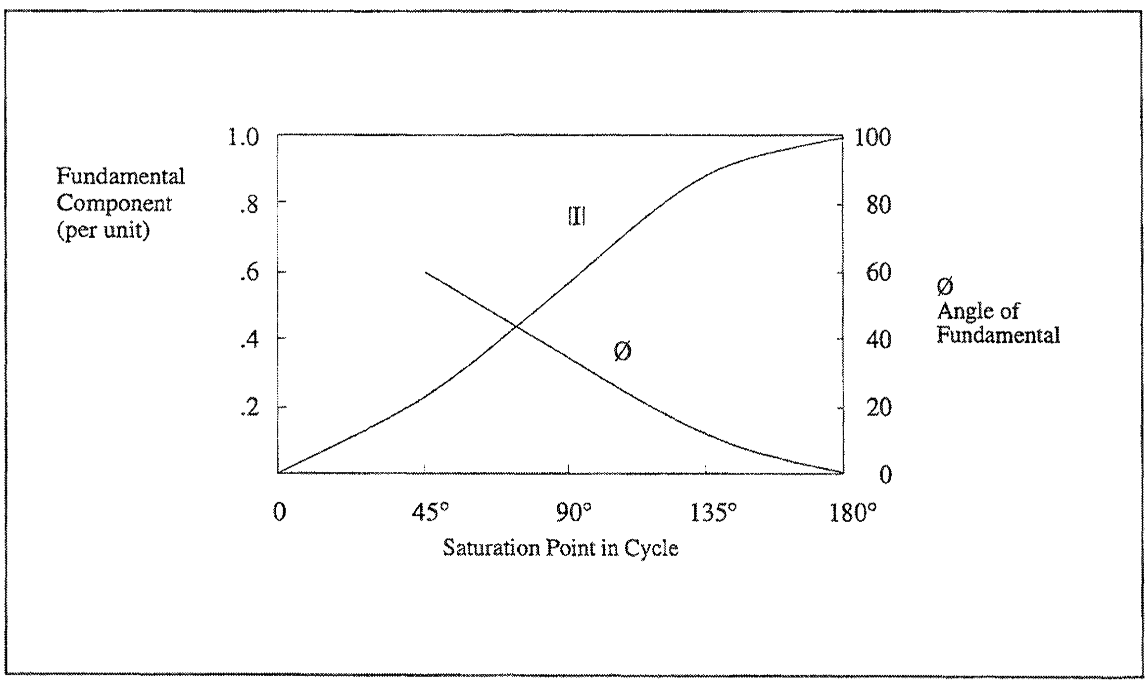

Figure 7. Fundamental Output of Ct During Symmetrical Saturation

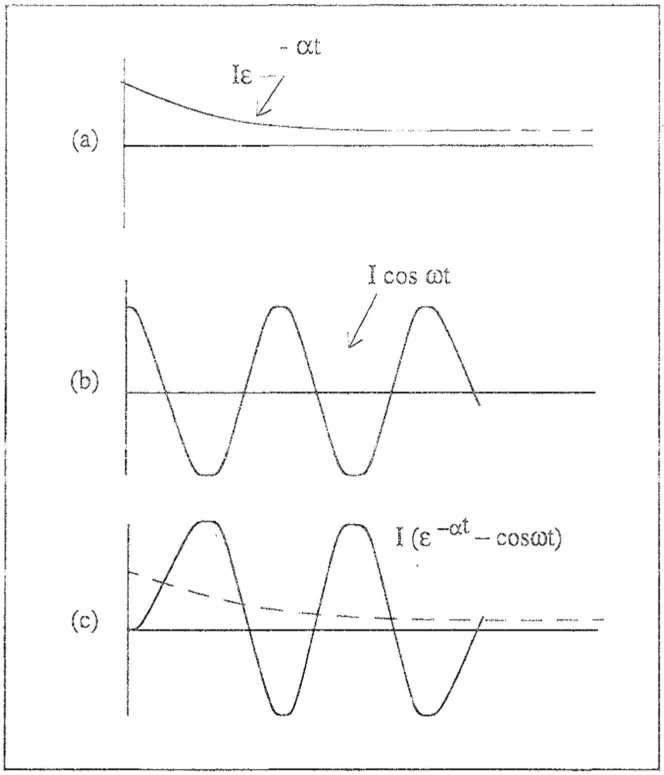

Figure 8. Fully Offset Current with Decaying dc

the measuring device in its entirety. Using 8 samples per cycle, there will be calculated a fundamental value of current. The decaying exponential will contain sine and cosine elements which will cause the measurement of the fundamental (60 hertz) component to have error in magnitude as well as angle. The extent of these errors is dependent upon T, the dc time constant and are shown in Figure 9. To minimize these errors, the first two samples are discarded before the Fourier products are produced.

Figure 9 indicates that an error no greater than 15% nor 5° is present following Fourier filtering.

Effect on Current Differential Scheme

This scheme is capable of misoperation upon the occurrence of ct saturation, but it is not very likely to do so. For external faults, with restraint being related (in the LCB-II and REL356) to the sum of the magnitudes of the local and remote filter output voltages, this restraint will be substantial. The operating quantity is the magnitude of the phasor sum. If now we ignore all but ct errors, and consider that one set transform without error and the ct's at the other end of the transmission line deliver a deficient current magnitude to the relays at that point, the behavior of the system may be examined by investigating the operating and restraint quantities:

$$V_{OP} = |V_{F1} + V_{F2}| \qquad (2)$$

$$V_R = 0.7[\ |V_{F1}| + |V_{F2}|\ ] \qquad (3)$$

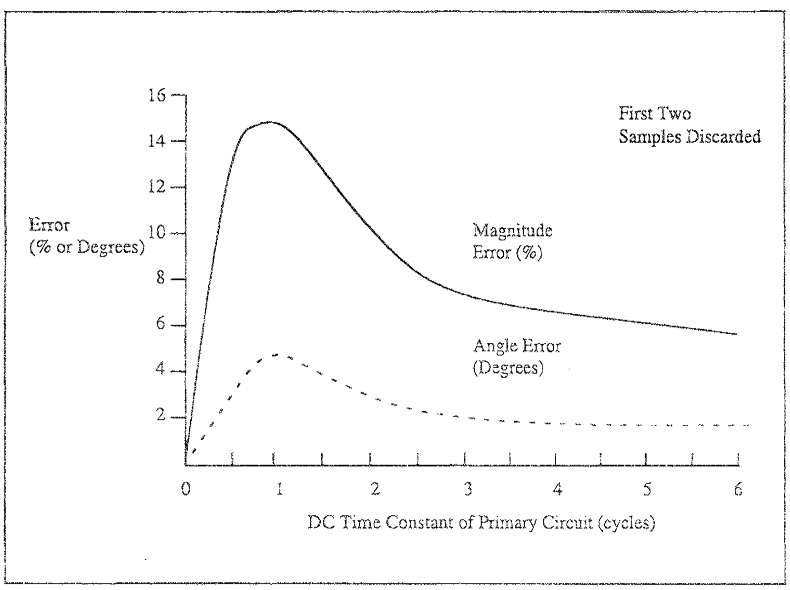

Figure 9. Influence on Fundamental of Max dc Offset Using Fourier Filter

If the deficient current for this external fault is 180° out of phase with the perfectly transformed current, I, at the other terminal and has a magnitude KI,

$$V_{OP} = |V_{F1} - KV_{F1}| = |V_{F1}(1 - K)|$$

and

$$V_R = 0.7[V_{F1}(1 + K)]$$

With some margin, the relay will reliably restrain under this consideration if:

$$0.7(1+K) > (1-K)$$

or $$K > 0.176$$

If the deficient current is now assumed to be at 90 degrees with respect to the perfectly transformed current, restraint is assured if K>0.246.

Thus it can be seen that current at the location where the deficient ct's exist may be as low as 25% of the current at the other terminal and still not misoperate for an external fault. The current differential relay is very secure in the presence of inequitable saturation.

Effect on Phase Comparison Relaying

Phase comparison relaying is influenced by ct saturation in many ways, depending on the nature of the scheme. One scheme (MSPC or REL350) will trip reliably at high speed for an internal fault if either terminal is able to trip before saturation occurs due to the dc component in the fault current. It then clamps to trip positive key, allowing the other terminal to trip for any positive (or zero) value current.

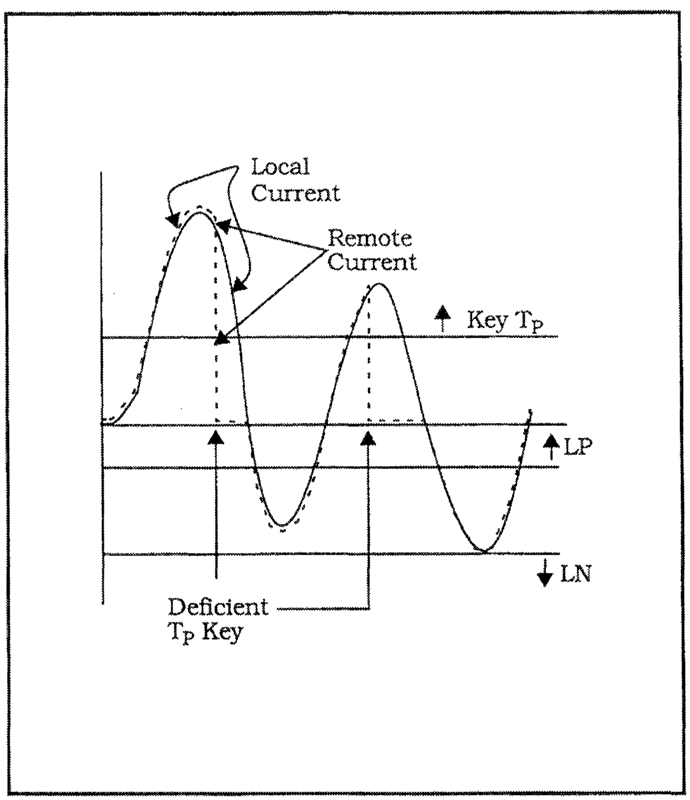

Figure 10. Effect of Different Ct Saturation on Offset Keying Phase Comparison - (Internal Fault)

An internal fault with severe saturation of the ct's at one terminal is shown in Figure 10. For the case shown, tripping occurs with considerable margin.

Even though saturation might occur, in a worse case, very early in the cycle, tripping of all terminals would still occur at high speed provided the ct's at one location deliver current to the relay with reasonable fidelity long enough to satisfy a 3 ms timer (4 ms for ground).

Figure 11 shows a case in which an external fault exists, offset keying is used and saturation of the ct occurs at one terminal only, because of the dc component of the fault current. Even with this severe difference in behavior of the ct's at the two terminals, the system is secure, though "holes" in the current permit undesired timing to take place.

Note that symmetrical saturation, Figure 6, may produce little effect on relays (such as the

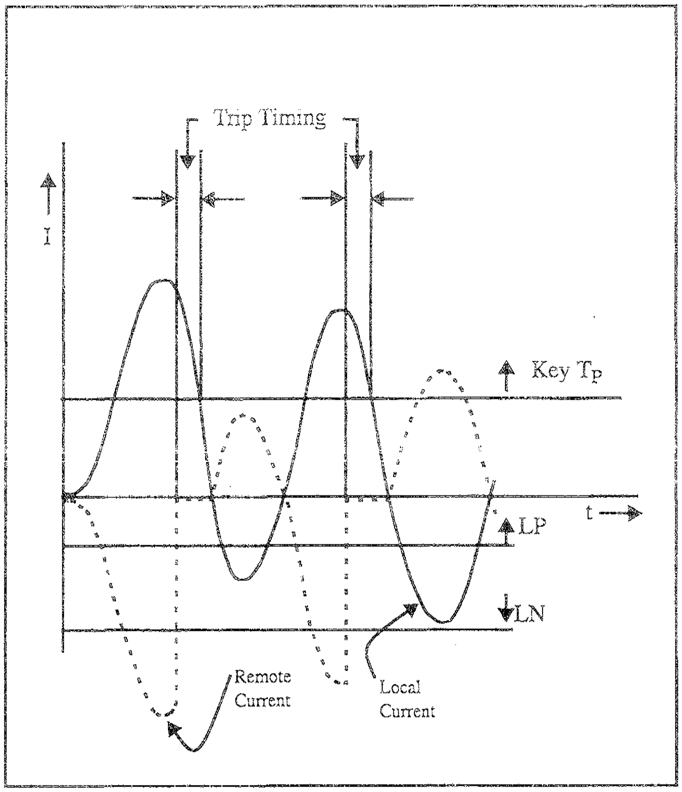

Figure 11. Effect of Different Ct Saturation on Offset Keying Phase Comparison - (External Fault)

REL350) which use a 240 hertz cutoff anti-aliasing filter because the fundamental only is presented to the sensing elements. Figure 7 describes the influence on this fundamental.

Effect on Distance Pilot Schemes

Current transformer deficiencies, in general, cause distance relays to see a lower effective current than they would otherwise see. This causes them to reach a shorter distance than they would if there were no ct saturation. Relays set to reach all faults on a protected transmission line will, in response to this effect, not fail to operate but rather will sense that the fault is farther away than it actually is. This will cause an electromechanical pilot distance scheme with minor ct saturation to trip perhaps as much as 10 to 20 milliseconds slower because of its dependency on energy level at the relay. A numerical relay encountering the same conditions will experience the same "reach-shortening" effect, but will not be subject to the operating time variations.

In a directional comparison blocking scheme, it is imperative that a "channel start" function take place at the terminal nearest the fault for all external faults for which the overreaching tripping relays at the terminal farthest from the fault are able to respond. Differences in ct performance at the two terminals can prevent the near "channel start" relay from operating for a fault for which the remote pilot trip relay operates. If this should happen a false trip will occur. This is attributable to the two different RMS current magnitudes delivered to the relays at the two locations. Directional overcurrent relays (tripping and carrier start) are more susceptible to this problem than are distance relays though both are vulnerable.

Microprocessor distance relays generally use a Fourier filter in isolating the fundamental component of current for distance measurement. Figure 9 depicts the influence of this treatment on the apparent fundamental (60 hertz) component of a current waveform such as that of Figure 8c. Precautions must be taken with Zone 1 relays to assure that the influence on the fundamental by the dc component is taken into account. The possible effect of a dc component on the fundamental is not nearly so extreme as its effect on the RMS value, to which other types of devices respond.

The appendix contains further thoughts on the choice of current transformers.

C. Coupling Capacitor Voltage Transformer Transients

CCVT's are excellent, economical substitutes for iron core voltage transformers. They do, however, introduce transients of their own, causing relays to receive voltage that is not truly indicative of that which is on the power system. In general, the higher the capacitance of the device, the better the fidelity of the transformation.

Effect on Current Differential Scheme

Current differential schemes use no voltage supply, and they are therefore not influenced by this phenomenon.

Effect on Phase Comparison

Basic phase comparison relaying uses no voltage input though some variations of this scheme have in the past required its availability, "Distance" phase comparison and "combined" phase comparison used distance relays, but they are not considered here. Modern phase comparison relays (such as REL350) contain a backup stepped distance system that is activated by the loss of channel. For time delayed trips the CCVT transient is not significant.

Effect on Distance Pilot

Blocking, unblocking and overreaching transfer trip schemes use, for their basic sensing function, overreaching, distance relays. The extent of the overreach is not critical, with the overreach set to assure that the worst CCVT transient still allows complete line coverage, there is no detrimental effect on this type of system. This may require a much longer reach setting on the overreaching relays than would otherwise be necessary. Since the zone 2 time trip function has a limited reach possibility, zone 2 and pilot trip distance functions should be independently settable.

Underreaching transfer trip relaying systems must have their zone 1 distance settings chosen in such a way as to avoid overreaching the next bus during the worst case CCVT transient. If this effect is too extreme, the zone 1 relays at the two terminals will fail to overlap, causing a hole to exist in the coverage by the pilot scheme.

D. Channel Problems

Relaying channels are quite diverse and experience noise, deterioration and failure. Any pilot system must be able to circumvent these problems by trip-blocking, error correction, or reverting to backup that is not channel dependent. Power line carrier uses the protected transmission line as part of its communications path. Faults on the line may not, but must be expected to, cause loss of channel. On-off carrier relaying systems use the off state as a trip condition (of course, accompanied by other logic). There is no normal transmission of carrier and no means of continuous channel monitoring.

Frequency-shift carrier continually transmits a "Guard" signal which can be supervised. Distance relays shift to a "Trip" state. Any inadequacy of the "Trip" state may not be detected during "Guard" transmission. Phase comparison relays continually shift from "Mark" to "Space". Faults may cause loss of channel.

Microwave, fiber-optic and pilot wire channels do not use the protected line as part of the communications path, but are subject to their own variety of reasons for failure.

Effect on Current Differential Relaying

Several options may be exercised when channel trouble is detected. The system may be allowed to revert to a simple overcurrent system with full advantage still taken of the symmetrical component filter, providing sensitive ground detection and suitably desensitized positive sequence detection.

If this is not desired, the system can reliably, automatically be removed from service until the channel is restored. This places total dependency during the channel outage on backup devices.

Effect on Phase Comparison Relaying

The basic phase comparison function is incapacitated when the channel is lost. Modern microprocessor phase comparison relays revert to 2 zone step distance backup when channel trouble is detected.

Power line carrier (on-off) phase comparison trips if a fault is detected and carrier becomes lost. Frequency-shift phase comparison operates with proper phase coincidence or for 150 ms following loss of channel (unblock logic), then followed by lockout of the relaying system. These systems are vulnerable to false trip when external fault detection and loss of channel occur simultaneously. Adequate line traps and adequately spaced drain coil and tuner gaps prevent this.

Effect on Distance Pilot Relaying

Blocking schemes must receive a carrier (or other) signal for external faults. POTT (Permissive Overreaching Transfer Trip) schemes must receive a signal from the other terminal for internal and external faults. Unblocking schemes must receive a signal from the other terminal for external faults.

Underreaching transfer trip schemes do not require the channel for any external fault security, nor for faults occurring in the usually substantial zone of overlap of the zone 1 relays. The channel is required only for end-zone faults to assure high speed tripping of both terminals.

Loss of channel is not detected immediately in a carrier blocking scheme. It is therefore more susceptible to false trip. POTT carrier schemes are susceptible to failure to operate in the event of channel problems.

E. Power System Swings

Swings occur following faults and switching, changing voltage and current are applied to the relays. Stable swings are self-correcting and **must** be ignored. Unstable swings require action at some locations and prevention of action at others. To do this on a discriminating basis is the goal.

Effect of Current Differential Relaying

Swings appear as "through" phenomenon and are ignored by these relays.

Effect of Phase Comparison Relaying

These relays also acknowledge swings to be an "external" phenomenon and restrain properly.

Effect on Distance Pilot Relaying

Distance relays may respond to the reduced voltage and increase current that they encounter during a swing. The ohmic trajectory that is manifested during a swing may be similar to S_1 or S_2 in Figure 12. Zone 1 is obviously less susceptible to operation on swings than the pilot distance relay $21P_A$, simply because of its smaller characteristic circle. Thus, the PUTT (Permissive Underreaching Transfer Trip) system is more secure than the POTT scheme against swing trips.

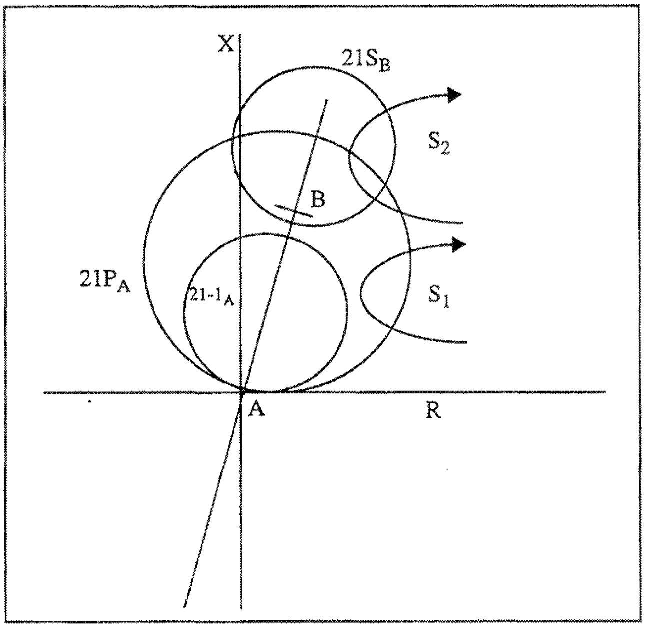

Figure 12. Influence of Swings on Distance Pilot Relaying

Swing S_2 enters $21P_A$ circle before it enters $21S_B$. For the blocking scheme, a false trip results. In the unblocking or POTT scheme, continuous transmission of a blocking signal from station B to station A is uninterrupted by this. These two schemes are, then, more secure than the blocking scheme and incidentally do it with less equipment (or fewer algorithms).

F. Three Terminal Lines

Three terminal lines inject the problems of possible outfeed for internal faults, infeed effects, possible weakfeed conditions, and channel complications.

Effect on Current Differential Relaying

The principal problem relates to the channel. Minimal contribution from one terminal to an internal fault or even small outfeed causes no problem with this system. The V_F voltage (equation 1) from each terminal must be transmitted to all terminals.

One terminal capable of delivering a large contribution to an internal fault is able to produce high speed simultaneous tripping at all terminals.

Effect on Phase Comparison Relaying

Because of the difficulty of comparing current phase relationship at one location with the phase angle of the phasor sum of the currents at the other two locations, this scheme is limited in its application.

With no outfeed possibilities, the on-off carrier scheme is usable, with all terminals tripping for internal faults during the off period. With frequency-shift systems, each transmitter must communicate continuously with both remote receivers, somewhat complicating the channel requirements. With outfeed at one terminal for an internal fault, this system is unsuitable.

Effect on Distance Pilot Relaying

The communications requirements are simplest in the carrier blocking schemes. The nature of the system is that the absence of carrier allows distance relays to trip. All of the carrier systems, then, operate at the same frequency. Only one receiver is required at each terminal. Any terminal requesting block gets it at all terminals. Any terminal having no current cannot block tripping at the other terminals. IF the maximum outfeed for an internal fault is smaller than the "starting" current level, the blocking scheme will trip correctly.

POTT and unblocking schemes use frequency shift channels. Since the trip frequency must be received (or the channel lost in the case of the unblocking system) when an internal fault occurs, all terminals must independently recognize the fault and send a trip request (shift to the trip frequency) to all terminals. Separate receivers for each remote terminal are required. Thus these systems have more complicated communications channels for three terminal applications and are dependent on all terminals being able to recognize internal faults.

PUTT systems bow to DUTT (direct underreaching transfer trip) systems where there is a weak source terminal. Any zone 1 relay operation keys to the trip frequency and without any distance relay operation at the two remote stations, immediate high speed tripping takes place at all locations.

This system is sensitive to the location of the tap for the third terminal, No zone 1 relay can be allowed to overreach any bus. A transformer at the tap often eases this problem.

G. Evolving Faults

Faults having one character initially and changing to a different state subsequently are difficult or impossible for relaying systems to handle. These faults may, after a short time, involve other phases or even other transmission lines. They initially may be external and become internal.

Effect on Current Differential Relaying

Current differential systems derive their operating quantity from the phasor sum of the symmetrical component filter outputs at the two terminals. Any combination of fault types involving a net internal fault contribution will produce tripping. However the use of the composite filter may produce difficulties with some combination of faults. An external ground fault simultaneous with an internal phase fault may produce undesired strong restraint to accompany the operating quantity. Zero sequence is usually heavily weighted compared to the positive and negative sequence weighting and may block tripping for the internal fault.

Effect on Phase Comparison Relaying

The segregated phase comparison system is without equal in this category. In an untapped transmission line, any current that is present in one phase at one terminal that is not present in the same phase at the other terminal is internal fault current or changing current, and there is no difficulty in distinguishing between the two. Any combination of internal faulted phases will be recognized as an internal fault ir-

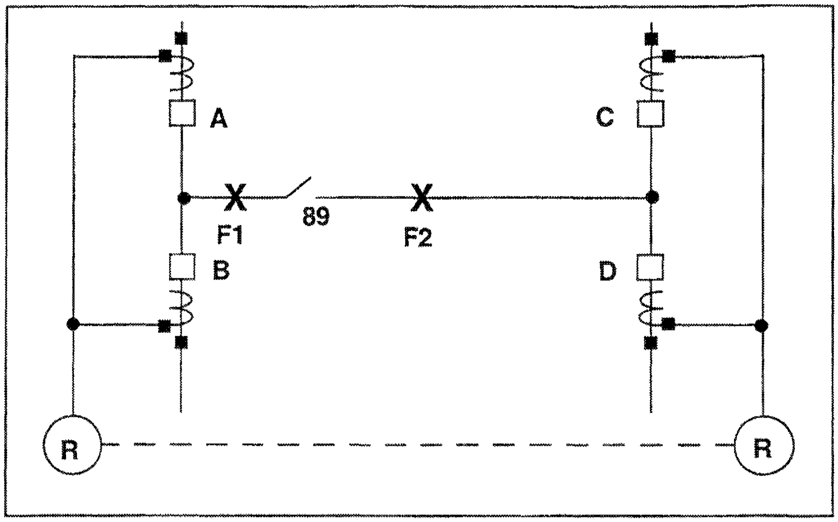

Figure 13. Pilot Relaying with 89 Open

respective of the involvement of the same or other phases in an external fault and irrespective of the presence of an internal or external series capacitor with or without flashed gaps.

Effect on Distance Pilot Relaying

Faults, evolving external to internal can be troublesome, possibly causing delayed recognition or even failure to trip. POTT schemes use a transient blocking scheme to make certain equitable resetting takes place during the current reversal that may occur due to sequential clearing of external faults. This requires the introduction of a trip time delay for internal faults following the establishment of transient blocking.

Simultaneous internal and external faults on different phases may produce inappropriate voltages for proper impedance measurement, and the distance relays may fail to trip.

H. Stub Bus Faults

With a line disconnect open in a two breaker scheme (ring or breaker and a half), such as shown in Figure 13, faults on the bus section between the breakers may be difficult to detect with a pilot relaying system. The line disconnect separates the two system segments, but the channel may still be intact. Faults occurring on one side of the disconnect will not be recognized by the relays on the other side. The necessary cooperation between terminals is lost. The qualification that an 89b auxiliary switch be available (on the line disconnect) makes several relaying systems suitable, whereas, otherwise their performance would be deficient.

Effect on Current Differential Relaying

With all breakers closed and 89 open, a fault at F1 will be recognized because of the generation of equal operating quantities at each relay. Breakers A and B are tripped to clear the fault. However, breakers C and D are also tripped even though no fault current is contributed through them. This undesirably splits the system. Options are available in this system (LCB-II or REL356) to prevent this and yet allow detection and clearing of faults F1 and F2 without overtripping. It requires an input to the relaying system of a "b" switch on device 89 to identify its opening. This "fails" the channel, to allow the relay at the far terminal to revert to overcurrent-only.

Effect on Phase Comparison Relaying

Microprocessor phase comparison relaying accepts the 89b input and generates and transmits to the remote station, a code to identify the open condition. With 89 closed, normal relaying takes place and faults F1 and F2 cause all four breakers to trip. With 89 open, F1 produces Tripping of A and B only, while F2 produces tripping of C and D only.

Effect on Distance Pilot Relaying

For a blocking scheme, discriminating tripping takes place even though 89 is open. F1 is cleared by opening A and B. F2 is cleared by opening C and D. Carrier transmission may take place for either fault due to the sensing of ΔV, but it will last only a short time (32 ms in one relaying system). For POTT and unblocking protective schemes, no tripping takes place with 89 open because, for example, F1 does not operate the overreaching distance relay at CD, and therefore transmission of the blocking (guard or space) signal from CD continues. This problem can be overcome by using the 89b contact. Received trip can be simulated locally when the 89b contact is closed to take care of fault F1. Keying to trip frequency by the 89b contact can arm the remote pilot system to be able to trip by distance relay operation for fault F2.

PUTT systems perform satisfactorily for all cases except a fault near 89 and outside of the zone 1 reach from CD. Fault F1 is cleared by zone 1 and the channel is keyed to trip. The permissive system requires that zone 2 at CD permit tripping. Since it does not detect fault F1, C and D properly remain closed. A direct underreaching protective system would overtrip for this same case.

I. Large Load and Limited Fault Current

In order for load to flow, there must be an angle between the positive sequence "sources" at the two ends of a transmission line. When an internal fault occurs, the contributions from the two ends of the line are out of phase. The extent of the influence is dependent upon the magnitude of the load flow and the length of the line.

Effect on Current Differential Relaying

Normally load is a "through" positive sequence phenomenon. Sensitive detection of a high impedance ground fault by weighting of the zero current effect may be masked by very large load flow, which continues during the internal fault. Positive sequence can be removed from the filter output by making $C_1 = 0$, but this then places dependence for 3 phase fault recognition on other devices. In general, the level of fault resistance that must be accommodated compared to the maximum value of load current is such that this need not be done.

Effect on Phase Comparison Relaying

A similar problem to that which exists for current differential is also present in phase comparison relaying. "Through" load current appears as outfeed. Essentially, for an internal fault, one end sees its fault contribution plus load current flowing into the line and the other sees, for an internal fault, its fault contribution minus load current flowing into the line. One form of segregated phase comparison relaying will respond correctly with 5 a of "through" load current and 1a of internal fault current. It also has a $3I_0$ subsystem that is not masked by load.

Effect on Pilot Distance Relaying

Load does not influence the reach of a distance relay at its maximum sensitivity angle. However, it will influence the polarizing voltage and with fault resistance, a substantial change in reach may occur. Overreaching occurs, in general, with load flow in the trip direction and underreaching occurs with load flow in the non-trip direction.

Very large load flow can get into the trip characteristic of distance relays that are responsive to positive sequence quantities and that are applied in long line applications. This is screened out as a standard course in microprocessor relays (such as REL302 and REL512) by utilizing a blinder element to block tripping for very large high power factor loads.

Overreaching applications (POTT, Unblock, Blocking) are not reach-sensitive and the load effect is generally not detrimental. PUTT systems are highly susceptible to misoperation or excessive shortening of coverage due to this effect.

In the presence of large load current, high resistance ground faults are best detected by sensitive zero or negative sequence overcurrent relays. Underreaching pilot systems require the use of a distance relay (or element, or algorithm) for the ground function. Sensitive ground detection is not compatible with zone 1 distance ground relaying.

J. Summary

Table 1 summarizes the influence of certain power system phenomenon on the most prominent pilot relaying systems. Some of the classifications are arguable, but those which are described as superior in the presence of certain transient conditions truly do have distinct advantages over other relaying systems, and those which are described as unsatisfactory do have serious shortcomings in the area described.

Among these systems that are described, none leaps out as being the overwhelming choice for all power system configurations, but the table should be of some help where certain difficulties are foreseen and relative behavior is being examined. The list of trouble sources is certainly not exhaustive, but the prevalent influences are covered.

Table 1: Pilot System Comparison

Performance in the Presence of:	Pilot System Type					
	Current Differential	Phase Comparison	POTT or Unblock	Blocking	PUTT	DUTT
Mutual	SUP	SUP	RSS	RSS	RSS	RSS
Ct Saturation	SAT	SAT(Q)	SAT	SAT(Q)	SAT	SAT
CCVT Transients	SUP	SUP	SAT	SAT	RSS	RSS
Channel Problems	SAT (Q)	SAT (Q) (with inherent backup) U (Composite Filter)	POTT - U UB - SAT (Q)	SAT (Q)	U	U
Swings	SUP	SUP	RSS	RSS	RSS	RSS
Three Terminal no outfeed	SUP	SAT (Q)	SAT (Q)	SUP	RSS	RSS
Three Terminal with outfeed	RSS	U	U	RSS	U	RSS
Evolving Faults	RSS	RSS (Composite Filter) SUP (SEG Ø)	RSS	RSS	RSS	RSS
Stub Bus	SAT (Q)	SAT (Q)	SAT (Q)	SAT	U	U
Load & High RG	RSS	RSS	SAT	SAT	U	U

SUP - superior
SAT - satisfactory
SAT (Q) - satisfactory but qualified
RSS - requires special study
U - unsatisfactory

CONCLUSION

Table 1 summarizes this paper. Each comment in the table is qualified and some power system configurations nullify the need for special study. The intent of the paper was to emphasize the strength and shortcomings of these limited number of pilot schemes in light of today's technology. Many variations of protective schemes exist and only a few have been compared. Among these few, none leaps out as being the overwhelming choice for all power system configurations, but the table should be of some help where certain difficulties are foreseen and relative behavior is being examined. The list in the table is certainly not exhaustive, but the prevalent influences are covered.

APPENDIX

The following observations may be made about current transformer choices.

[1] The ct ratio, where possible, should be chosen to deliver to the relays no more than 100A, RMS symmetrical secondary for an external fault.

[2] The ct's should be chosen so saturation will not occur for the highest internal fault current foreseen for a period of time long enough for the protective relays to trip and seal.

[3] The burdens on the ct's at the two terminals should be approximately the same, so saturation will occur at essentially the same time for external faults.

[4] The burden on each ct should be no more than the ANSI (or IEC) standard burdens for the ct chosen. (C800, 8 ohms; C400, 4 ohms etc.)

BIOGRAPHICAL SKETCH

Walter Elmore was born in Bartlett, Tennessee, became a Navigator in the Air Force and graduated from the University of Tennessee with a B.S.E.E. in 1949. He was in Substation Design at Memphis Light Gas & Water Division until he joined Westinghouse Electric Corp. in 1951 as a District Engineer in Seattle, Washington. He transferred to the Relay-Instrument Division in Newark, New Jersey in 1964 where he later became Manager of the Consulting Engineering Section. He held that position, following a 1989 merger with ABB, until 1992 in Coral Springs, Florida. From 1992 until 1996, when he retired, he held the position of Consulting Engineer. He continues to work as a Consulting Engineer for ABB.

He is past chairman of the IEEE/PES Technical Council, past chairman of the IEEE/PES Power System Relaying Committee and is a Life Fellow of the IEEE. He is a member of Phi Kappa Phi, Eta Kappa Nu, and Tau Beta Pi honorary fraternities. He received the 1989 IEEE Gold Medal for Engineering Excellence, and the 1989 Power System Relaying Committee Award for Distinguished Service. In 1996, the ABB manufacturing plant in Coral Springs, Florida was dedicated to him. In 1997 Texas A&M presented him with The Most Prolific Author Award. He was accepted as a member of The National Academy of Engineering in 1998. He has presented over 100 Technical papers, holds 5 patents and is the editor of the book, "Protective Relaying Theory & Applications." He is a registered Professional Engineer in the State of Florida.

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