Reprint

Of

Two Technical Papers Presented

At The

IEEE Power Engineering Society Winter Meeting

New York Hilton Hotel

Thursday, January 30th, 1992

CHARGE COMPARISON PROTECTION OF TRANSMISSION LINES - RELAYING CONCEPTS

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Transactions on Power Deleivery; Volume 7, Number 4, Pages 1834 through 1860; October 1992

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Abstract - Charge comparison is a new transmission line protection system. It is a form of current differential relaying. Charge comparison largely resolves the traditional problems of current differential relaying of transmission lines: protection is lost if channel fails, large channel capacity required and precise channel delay compensation required. This new technique is suitable for the protection of two - or three-terminal ac transmission lines, of all lengths and voltage levels, with or without series or shunt compensation, with three-pole or single-pole tripping.

Keywords - Charge comparison, Current differential relaying, Transmission line protection, Digital relaying.

Note - At the time of the writing of this paper, the development planning for three-terminal line protection and single-pole tripping has been done, but the actual hardware and software designs of these functions have not been accomplished. Therefore, any comments in this paper regarding these functions are purely conceptual.

INTRODUCTION

A new transmission line digital protection system, including relaying and communications, has been developed. This system, called charge comparison, is based on the principle of conservation of charge. This paper will describe the relaying concepts of charge comparison. A related paper describes the communications concepts [1].

CURRENT DIFFERENTIAL VS. DIRECTIONAL COMPARISON

Since charge comparison is a form of current differential relaying, it is useful to review, in very general terms, the relative strengths/weaknesses of current differential relaying of transmission lines, when compared with the more traditional method of communications - based protection of transmission lines: directional comparison schemes using distance relays and directional overcurrent relays.

Disadvantages of Current Differential Relaying

Critical

1. Protection lost if channel fails.
2. High-capacity channel required, particularly if each phase is protected separately.
3. Precise channel delay compensation required.

92 WM 209-7 PWRD A paper recommended and approved by the IEEE Power System Relaying Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1992 Winter Meeting, New York, New York, January 26 - 30, 1992. Manuscript submitted July 15, 1991; made available for printing December 10, 1991.

Less Critical

4. Does not provide fault-locating.
5. Cannot serve as ac voltage remote for data acquisition (since relaying operates from current - only).
6. Does not provide remote bus fault time-delayed backup.
7. Does not trip for unstable swings.
8. Difficult to apply on tapped lines.

The three critical disadvantages have been decisive factors in the traditional overwhelming preference for the directional comparison schemes [2]. The other disadvantages have been relatively less important, for the following reasons:

Numbers 4. and 5. relate to secondary functions, not the primary function which is fault protection.

Number 6. is often not significant since many relay engineers prefer local backup for bus fault protection [3].

Number 7. is actually more an advantage than a disadvantage for current differential relaying. Increasingly, relay engineers prefer inherent blocking of the line fault protection during swings, with voltage-angle-controlled breaker tripping at selected locations, using voltage phase comparison [4], R/R-dot [5], or other techniques that are independent of the fault sensing relays.

With regard to Number 8., tapped lines can often be protected by current differential relaying, with reduced phase/ground sensitivity. These lines can also present limits to distance-based schemes.

Advantages of Current Differential Relaying

On the other hand, there are numerous relative advantages of current differential relaying (particularly if the protection is on a per-phase basis) when compared to the distance-based schemes:

* Not subject to the transient response problems associated with capacitive voltage transformers [6].
* Not subject to blown potential fuse problems.
* Zero-voltage faults not a problem.
* Not subject to the relaying voltage problems associated with short lines with high source-impedance-ratios: small relaying potential causing poor signal-to-noise ratio [7].
* Not subject to ferroresonance problems which may occur with potential transformers [8].
* Not affected by line-side potential providing spurious voltage to relays protecting a deenergized line, with coupling to a parallel energized line.
* Unaffected by voltage inversions associated with series compensated lines [9].
* Per-phase current differential protection operates correctly for single-pole tripping schemes, particularly during the difficult double-circuit flashover condition [10] and during the single-phasing interval.
* Unaffected by series impedance unbalance (due to unequal pole operations, unequal gap flashing on series compensated lines, etc.) causing misoperation of directional overcurrent ground relays [11].
* Security during current reversals due to sequential clearing of parallel line faults not a

problem. For per-phase schemes, this implies high speed tripping (without the current reversal security delay associated with directional comparison schemes) for evolving faults.

* The per-phase scheme, including separate residual current differential, handles outfeed conditions on two-terminal lines, due to high resistance ground faults with heavy through load.
* Correctly trips for the internal fault with outfeed at one terminal that may occur on three-terminal lines [12].
* Unaffected by infeed on three-terminal lines causing change in effective reach of distance relays [12].
* Unaffected by mutual induction from parallel lines causing loss of directionality of zero-sequence polarized ground directional relays and change of effective reach of ground distance relays.
* Inherently provides stub-bus protection, without requiring disconnect switch auxiliary contact control [13].
* Inherently blocks during swing conditions, allowing voltage-angle-controlled separation at preselected locations.
* Unaffected by the short-line problems of distance relays due to magnified arc resistance and ground fault resistance relative to line impedance [14].
* The per-phase current differential schemes inherently phase-identify all faults, allowing three-phase fault reclose blocking and other phase-identification-related functions, such as control of dual breaker failure timers (fast timer for multi-phase faults).
* Simultaneous high-speed tripping of all terminals, even for high resistance ground faults near strong terminal where the weak terminal sees essentially no fault current at all (due to infeed effect at strong terminal), until the strong terminal trips.
* Can tolerate increased line loading without affecting relaying characteristics or requiring relay setting changes.

<u>Summary of Disadvantages and Advantages</u>

Except for the three critical disadvantages, it is clear that current differential has more relative strengths than weaknesses. The remainder of this paper will address the resolution of these three critical problem areas of current differential relaying of transmission lines.

USE OF ACCURATE TIME-OF-DAY CLOCKS

The third critical disadvantage of current differential protection of transmission lines has been defined as the requirement for precise channel delay compensation. One relatively simple solution to this problem would be accurate (sub-millisecond) time-of-day clock time-tags at each terminal. Satellite communications, fiber optics, or other means could provide these accurate time-tags, which would be transmitted between terminals along with the current information. This would enable exact time matching to determine difference current [15].

After review, the time-of-day approach was ruled out in the development of the new relay system. Reasons:

* In the near future, accurate time-of-day sources will not be available at all substations where the new relay system would be considered for line protection.
* Even when these timing sources are universally available, the reliability of protection using time-stamps would be dependent on the satellite, or other, communications at each station, in addition to the bi-directional communications between stations.

POLAR DIAGRAM ANALYSIS OF CURRENT DIFFERENTIAL RELAYING

In order to resolve the three critical disadvantages of current differential relaying of transmission lines, a general analysis of this form of relaying should first be made. The polar diagram is a useful tool for this purpose. Consider a two-terminal line, with the local current taken as the reference phasor. Arbitrarily assume that 0° current points straight down on the polar diagram, with conventional (counterclockwise) phase rotation. Further, assume that the local reference current is always at 0°. The remote current (or phasor sum of remote currents, in the case of three-terminal lines) is then plotted for various power system conditions. Figure 1 shows the remote current, prior to transmission over the communications channel (i.e., without any errors that may be introduced by the channel).

It is emphasized that Figures 1.d and 1.e (high resistance ground fault, with outfeed due to load current) apply only to per-phase current differential schemes. Single-phase composite quantity schemes, using summation transformers or sequence networks, produce composite voltages that combine

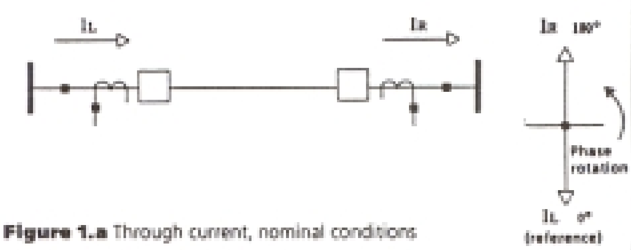

Figure 1.a Through current, nominal conditions

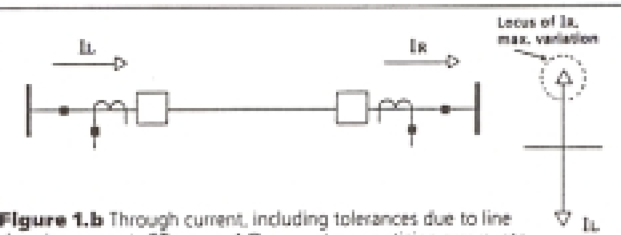

Figure 1.b Through current, including tolerances due to line charging current, CT errors, A/D converter quantizing errors, etc. (not including errors introduced by communications channel)

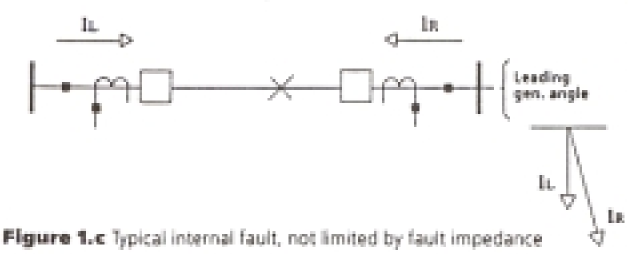

Figure 1.c Typical internal fault, not limited by fault impedance

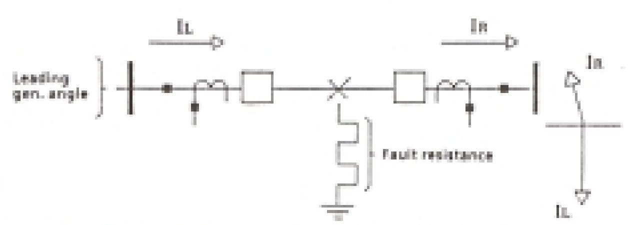

Figure 1.d Internal fault with outfeed (local terminal is sending end)

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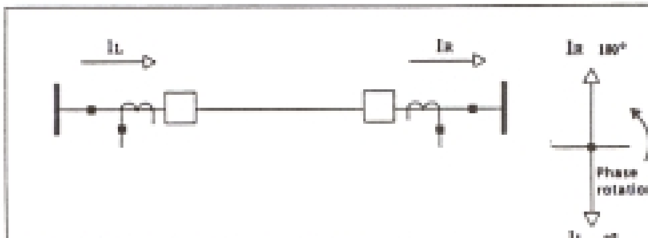

Figure 1.a Through current, nominal conditions

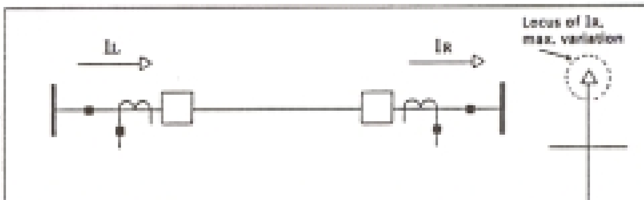

Figure 1.b Through current, including tolerances due to line charging current, CT errors, A/D converter quantizing errors, etc. (not including errors introduced by communications channel)

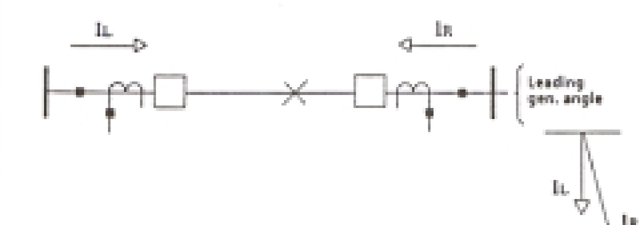

Figure 1.c Typical internal fault, not limited by fault impedance

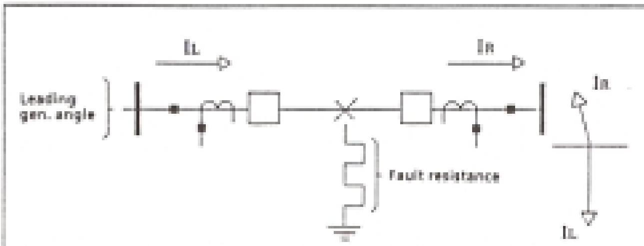

Figure 1.d Internal fault with outfeed (local terminal is sending end)

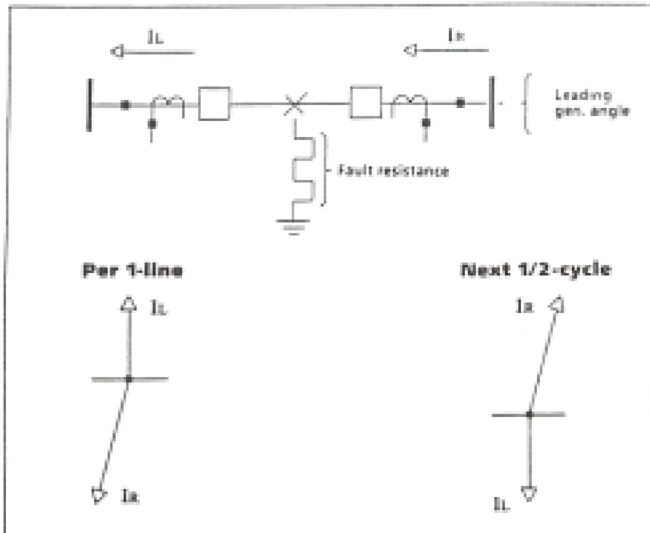

Figure 1.e Internal fault with outfeed (Remote terminal is sending end)

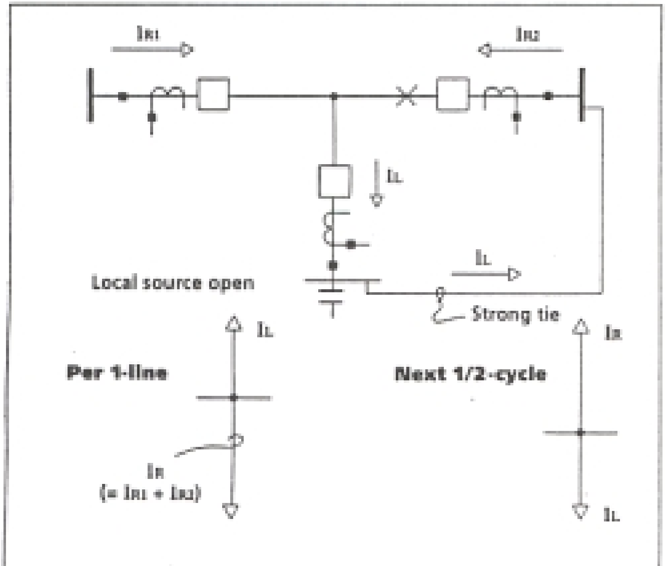

Figure 1.f Three-terminal line, internal fault with outfeed at local terminal

the effects of high resistance fault currents and load currents at variable angles with respect to each other. This is because the load current effect is always referenced to the same phase, while the fault current effect depends on which phase is faulted. This makes Figures 1.d and 1.e sometimes incorrect for these composite quantity schemes. On the other hand, the high-impedance ground fault current, which is always resistance-limited, is essentially in-phase or out-of-phase with the load current on the faulted phase. This accounts for the approximately co-linear relationship between I_L and I_R in Figures 1.d and 1.e.

Figure 1 shows the remote currents prior to transmission over the communications channel. The channel introduces possible errors in the remote current, as perceived by the relay at the local station. These errors are mostly in phase angle, not magnitude. This is because the communications channel transfer function of magnitude tends to be quite accurate for both FM and digital communications. On the other hand, the transfer function of phase angle depends on the accuracy of channel delay compensation. For example, Figure 2 illustrates the effect of improper channel delay compensation on the perceived remote current, for the through current condition (load, external fault or system swing) of Figure 1.a.

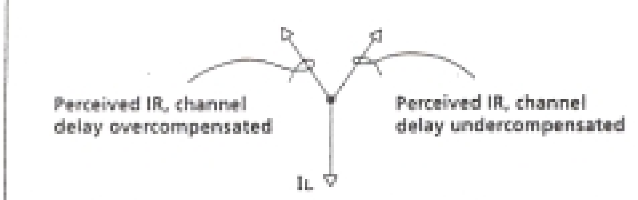

Figure 2. Through current with incorrect channel delay compensation

Conventional Current Differential Relays

The design approach for conventional current differential relays for transmission line protection has been to emulate the performance of the traditional current differential relays that have been used for apparatus (generator/transformer/bus/motor) protection, as illustrated in Figure 3. When protecting transmission lines, communications channels (pilot wire/microwave/fiber optics/etc.) replace the current transformer (CT) secondary cables for the purpose of delivering the remote current information.

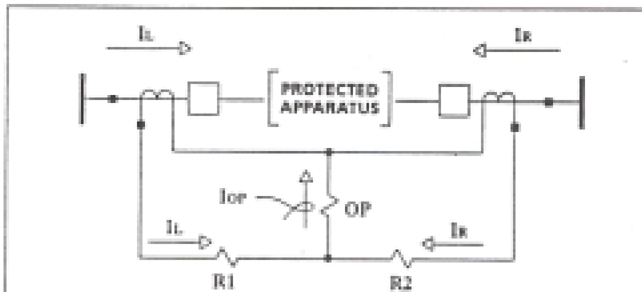

Figure 3. Traditional current differential relay for apparatus protection

The operate current of Figure 3 is the phasor sum of the local and remote currents. Restraint coils R1 and R2 (R2 is optional) provide increased restraint as the current levels get bigger. This provides security in the face of unequal current transformer saturation and incorrect channel delay compensation, both of which are errors which increase as current levels become higher.

In order to emulate the proven apparatus protection circuit of Figure 3, conventional current differential relays for line protection must transmit complete replicas of the current phasors (magnitude and phase angle) between terminals. This has yielded the conventional polar diagram restraint circle characteristic of Figure 4. This characteristic results directly from the circuit of Figure 3.

If the remote current plots within the circle of Figure 4, the relay restrains. If the remote current plots outside the circle, the relay operates. For transmission line applications, this conventional restraint circle has always presented a dilemma:

* To tolerate the effect of line charging current and relay system errors, particularly due to incorrect channel delay compensation as illustrated in Figure 2, the restraint circle should be large

to prevent false tripping during through-current conditions.
* To provide good sensitivity for internal faults with outfeed (see Figures 1.d, 1.e and 1.f), the restraint circle should be small.

Because of this dilemma, alternative techniques should be considered.

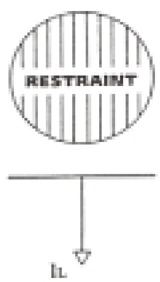

Figure 4. Polar diagram operating characteristic, traditional current differential relay

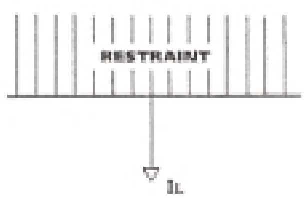

Figure 5. Phase comparison operating characteristic

<u>Phase Comparison</u>

One alternative would be phase comparison. When plotted on a polar diagram, the traditional phase comparison scheme (small magnitude square wave threshold and 90° coincidence threshold) has a characteristic per Figure 5. If the remote current plots in the upward direction, the relay restrains. If the remote current plots downward, the relay trips.

Conventional phase comparison has good tolerance for improper channel delay compensation, but cannot handle the outfeed conditions of Figures 1.d, 1.e and 1.f. Also, since phase comparison does not respond to magnitude, it cannot introduce more magnitude restraint at higher currents to counter the effect of unequal CT saturation. Also, phase comparison has trouble handling weak/zero infeed conditions, where high frequencies can "poke holes" in the square waves being transmitted.

<u>Note</u> - Phase comparison with offset keying provides partial improvement for the above conditions [9].

<u>Magnitude Comparison</u>

Since phase comparison has certain strengths and weaknesses, it is appropriate to also examine magnitude comparison, which is the mirror image of phase comparison. This scheme senses current magnitude differences only and is blind to any phase angle differences (the exact opposite of phase comparison). The polar diagram characteristic is shown in Figure 6.

If the remote current plots in the shaded area inside the ring, the relay restrains. All other areas produce tripping. Some observations regarding Figure 6:
* The response of the relay in the unshaded areas is totally correct. The restraint ring is made wide enough to provide a security margin to account for any magnitude differences due to line charging current and magnitude errors in the protection system (CT's, auxiliary CT's, analog-to-digital converters, etc.). For high currents, where unequal CT performance may occur, the ring would be much wider to provide security.
* The response of the relay in the shaded region is sometimes correct and sometimes incorrect. Remote currents that plot inside the top of the ring are certainly external faults (or through currents due to load or swings) and <u>correctly</u> restrain. Remote currents that plot inside the bottom of the ring clearly are due to internal faults, and therefore <u>incorrectly</u> restrain.

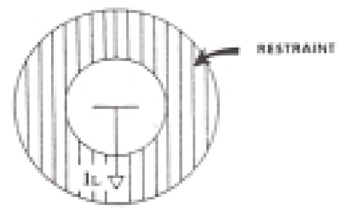

Figure 6. Magnitude comparison, operating characteristic

Since there is ambiguity about the performance of the magnitude comparison relay for remote currents that plot inside the ring, a further observation is now made about these conditions:
* Remote current, prior to communications channel transmission, that plots in the ring between the top and bottom regions <u>cannot exist</u>. (See Figure 7).

Figure 7. Magnitude comparison, remote currents prior to communications channel transmission

Some conditions regarding the above observation:
* This statement applies only to per-phase current differential relays, since the <u>effective</u> remote current for composite quantity schemes can plot in the in-between region for some high resistance ground faults.
* Internal faults during system swings can plot in the in-between region, depending upon generator angle difference. More about this later.

To prove that remote currents cannot plot in the in-between region, a detailed study was made. The study shows only one case, other than the internal fault during a system swing, that violates this rule: a transmission system with 90% or more series compensation and an internal high resistance ground fault. Since series compensation above about 70% is not used, this exceptional case was ruled out as unrealistic.

<u>Perceived Remote Currents</u>

Figures 1 and 7 show remote currents prior to communications transmission. As previously discussed (see Fig. 2), incorrect channel delay compensation introduces an angular shift in the perceived remote currents (see Figure 8).

The ideal relay system would treat the perceived through current region the same as actual through current. Similarly, the perceived internal fault region should be treated the same as an actual internal fault. The borders between through current and internal fault are the heavy horizontal lines of Figure 8.

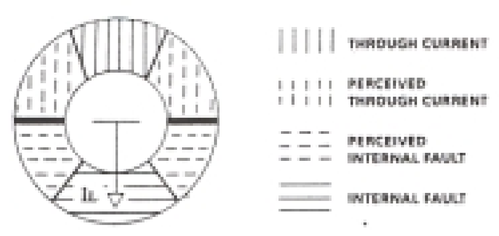

Figure 8. Perceived remote currents in the equal magnitude ring

Ideal Polar Diagram Relay Characteristic

Since the lower half of the ring is treated as a trip (i.e., internal fault) region, it may be merged with the unshaded (trip) region of the magnitude comparison relay (Fig. 6). This results in the ideal rainbow-shaped polar diagram characteristic shown in Figure 9.

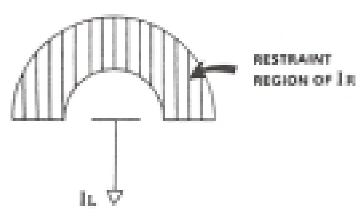

Figure 9. Ideal polar diagram characteristic

Note - As previously stated, the characteristic of Figure 9 may cause failure to trip for internal faults during system swing conditions. Trip attempts during these wide angle conditions could damage the circuit breaker, so this failure to trip is actually desirable. In this case, tripping would occur when the generators swing further to become more in-phase.

The rainbow characteristic of Figure 9 essentially solves Disadvantage Ø3 of current differential relaying of transmission lines, since it tolerates improper channel delay compensation (up to ± 4 ms) without misoperation, for external and internal faults. The rainbow characteristic also improves the sensitivity during outfeed conditions (high resistance ground faults with through load and three-terminal line faults with outfeed). This improvement in sensitivity as well as security, when compared with the conventional circle characteristic, is illustrated in Figure 10.

OPERATION OF CHARGE COMPARISON

The rainbow-shape has been shown to be the ideal polar diagram characteristic. As will now be demonstrated, charge comparison provides this characteristic. (The basic operation of charge comparison has been patented [16].)

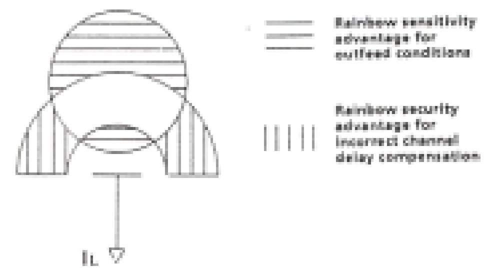

Figure 10. Rainbow vs. conventional circle

To perform charge comparison, the current wave of each phase and residual is sampled every 1/2 ms. The half-cycle area under each wave is measured by integrating current samples between zero-crossings. For each phase and ground, the resulting ampere-second area (i.e., coulombs of charge) is stored in local memory, along with polarity and start/finish time-tags. This storage operation occurs only if the magnitude exceeds 0.5 ampere rms equivalent and the half-cycle pulse width is equal to 6 ms or more.

Note - Magnitude is actually measured in terms of ampere - seconds (i.e., coulombs). However, all values are converted to amperes rms equivalent, based on a perfect 60 Hz sine wave, without offset. Current values in this paper are secondary currents, based on current transformers rated 5 ampere.

Every positive (negative for 3Io) magnitude is also transmitted to the remote terminal, along with phase identification and some timing information related to pulse width and queuing time (if any) at the transmitting terminal. When the message is received at the remote terminal, it is immediately assigned a received time-tag. A time interval is then subtracted from the received time-tag. This interval represents the channel delay compensation (which does not have to be precisely equal to the actual channel delay time) and the timing information contained in the received message. The adjusted received time-tag (after subtraction) is then compared with the local start and finish time-tags, looking for a "nest", per Figure 11 (shown for an external fault).

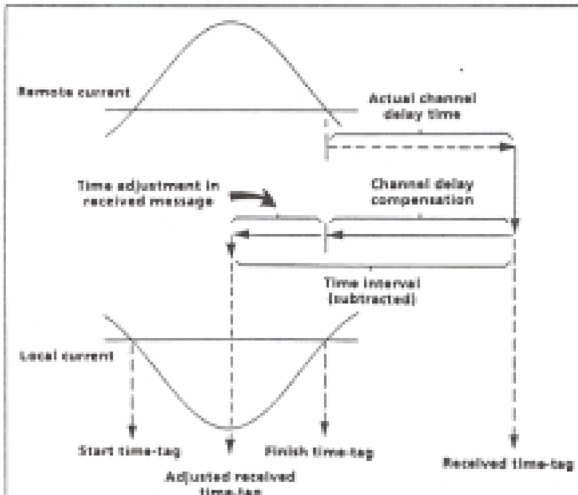

Figure 11. Operation of charge comparison, external fault

A nest is achieved when the adjusted received time-tag is greater than the local start time-tag and smaller than the local finish time-tag, for a given half-cycle stored in memory.

When the nesting operation is successful, the local and remote current magnitudes (actually charges converted to equivalent currents) are then added to create the scalar sum (sum of absolute magnitudes) and arithmetic sum (absolute magnitude of the sum of the signed magnitudes). The scalar sum becomes the effective restraint quantity and the arithmetic sum becomes the effective operate quantity, per the bias characteristic shown in Figure 12.

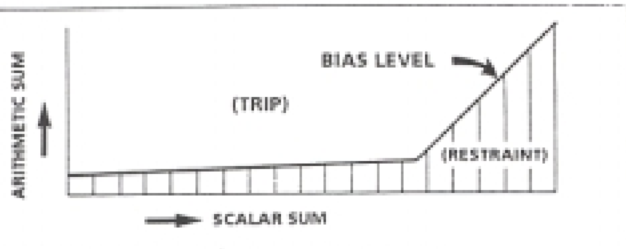

Figure 12. Bias characteristic of charge comparison

The bias level is an operate threshold which provides security in the presence of spurious operate current due to line charging current, current transformer mismatch, analog-to-digital conversion quantizing errors, etc. As shown in Figure 12, the bias level rises sharply after the scalar sum reaches a high value. This provides security for unequal CT saturation during high current external faults. At lower currents, the bias level has a slight upward slope. This takes care of the relatively minor non-communications-related errors that increase with current level, such as CT ratio errors.

The operating characteristic of charge comparison, when plotted on a polar diagram, is in fact the ideal rainbow-shape of Figure 9. Referring to Figure 11, if the adjusted received time-tag nests with a local negative half-cycle, this is equivalent to the upper half of Figure 9. If the adjusted received time-tag nests with a local positive half-cycle, then the arithmetic sum and scalar sum are equal to each other, which describes a 45^0 line on the bias characteristic (well above the bias threshold for all current values, except very small). This is equivalent to the lower half of Figure 9.

The bias level of charge comparison is significantly more sensitive than that of conventional current differential relays for line protection, per Figure 13. The conventional relay requires a gradually increasing bias to take care of increasing spurious operate current for a given assumed error in channel delay compensation (the biggest single source of spurious operate current). In contrast, charge comparison introduces no additional communications-related error, at all, as the currents get bigger for a given error in channel delay compensation. Furthermore, for a given magnitude of through current, no operate error current is introduced, at all, for increasing channel delay compensation error (up to ± 4ms, at which point a total relay misoperation occurs - typical of a digital system). The ± 4ms misoperating threshold for charge comparison is almost three (3) times the ± 1.5ms (approximately $\pm 30^0$) misoperating threshold which is typical of conventional current differential schemes (with circular polar diagram characteristic of Figure 4).

Resolving Two of the Critical Disadvantages of Current Differential Protection

As shown, the charge comparison technique provides a rainbow polar diagram characteristic. Furthermore, charge comparison requires minimal communications channel capacity, since a single message is sent once per cycle, per phase. A 7.2 kbps modem, suitable for transmission over an analog voice circuit, provides the necessary channel throughput for charge comparison of all three phase currents and residual current. In contrast, conventional current differential schemes must replicate the entire current phasor, which requires a wide-band channel capacity for per-phase protection.

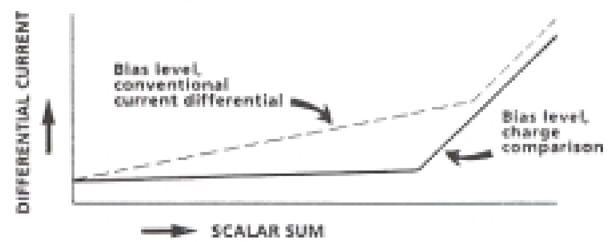

Figure 13. Bias level, charge comparison vs. conventional current differential

In summary, charge comparison essentially overcomes the 2nd and 3rd critical disadvantages of current differential schemes: channel capacity and channel delay compensation.

Theoretical Basis of Charge Comparison

Charge comparison is based on the principle of conservation of charge at a node. This is also the principle from which Kirchhoff's Current Law (the theoretical basis of current differential relaying) is derived.

Adverse Side-Effects of Charge Comparison, and How they are Resolved

Although charge comparison largely overcomes the 2nd and 3rd critical disadvantages of current differential relaying, it introduces some side-effect problems of its own:

* Inherently slow, since must wait for a zero-crossing at the finish of the positive half-cycle of phase current (negative for residual) before transmitting charge information to the remote terminal.
* Totally dependent on zero-crossings, and requires at least 6ms half-cycle pulse width. This means the scheme is unable to trip for corrupted (high-frequency) currents at one terminal, which may occur for some weak/zero feed situations, per Figure 14, taken from Ref. [17].

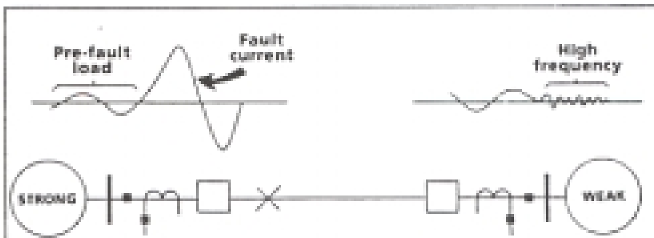

Figure 14. Internal fault with weak/zero infeed

* Must wait a very long time (therefore, very slow) if an internal fault with fully offset current wave occurs near a generating station and does not experience any zero-crossings for several cycles, per Figure 15, taken from Ref. [18].

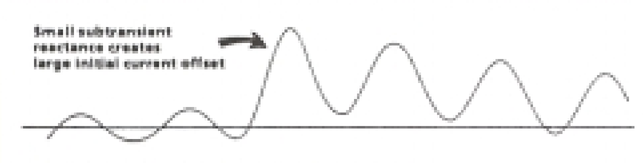

Figure 15. Internal fault, delayed zero-crossing

* An external fault could produce a current wave which has a double excursion which barely crosses the zero-axis at one terminal and just fails to cross the zero axis at the other terminal (per Figure 16). This could cause a false trip.

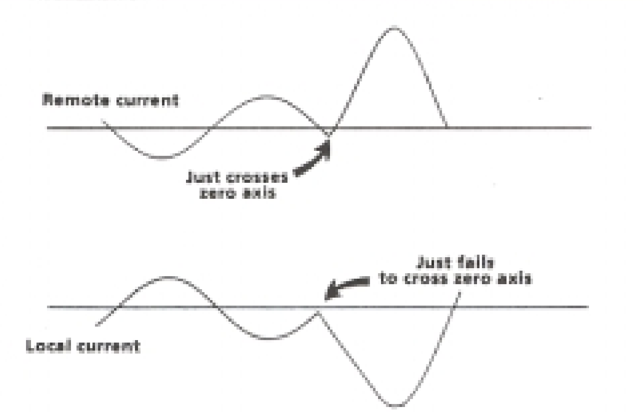

Figure 16. Double excursion security problem

Charge comparison addresses these side-effect problems as follows:

* Each phase current and 3Io are compared separately. Phase currents are transmitted for positive half-cycles, only. Residual current is transmitted for negative half-cycles, only. This provides protection on every half-cycle for all internal faults [19].

* Charge comparison includes a "UHS" (ultra-high-speed) trip circuit that has priority interrupt any time the local current exceeds 12A peak for more than 2ms. This allows the relay to reach a trip decision in as little as 5ms for wide-band applications (fiber optics or 56kbps digital) or about 16ms for voice grade channel applications. The actual trip signal to the breaker requires another 4ms for operation of a multi-contact trip auxiliary relay.

* Charge comparison includes a "weak-feed" circuit that operates any time the local current is less than 1.5A rms, regardless of frequency or phase angle, and the received magnitude from the remote terminal is 4A, or greater.

* The UHS circuit,previously described, solves the full-offset-without-zero-crossings problem, since this condition only occurs right near a major generator and therefore always involves high current well above the 12A peak level of the UHS circuit.

* Charge comparison includes an inhibit circuit that prevents false trips during the double-excursion condition. If this circuit detects a dropping current that fails to cross zero, it blocks tripping.

SOLVING THE FIRST DISADVANTAGE OF CURRENT DIFFERENTIAL RELAYING

At the start of this paper, the first critical problem of current differential relaying of transmission lines was described as: Total loss of protection whenever the channel fails. Overcurrent protection may be enabled whenever the channel fails, but this is considered to be relatively ineffective protection, particularly when compared to the non-pilot distance relay backup which is inherent with the directional comparison schemes.

In order to overcome this problem, charge comparison provides protection during channel failure by multiple techniques, including channel redundancy and loss-of-load protection. An overview of these techniques is provided below. More details about channel redundancy are provided in Ref. [1].

CHANNEL BACKUP, TWO-TERMINAL LINES

Single Channel Configuration

This involves a single 4-wire bi-directional communications channel (voice, wide-band digital or fiber). If the channel is lost in both directions, then a built-in overcurrent backup system is the only protection available. This consists of high-set overcurrent relays, loss-of-load and switch-into-fault circuits. If the 4-wire (or 2-fiber) channel can be separated in such a way that the outgoing and return channels are usually not subject to common mode failures, then loss of channel in just one direction will allow charge comparison clearing at one terminal and sequential clearing at the other terminal by loss-of-load, provided there is pre-fault load current and the fault is not three-phase.

Loss-of-Load

This is an old technique that has recently been revived [13]. Loss-of-load senses the interruption of load current on the unfaulted phase(s) due to the clearing of the remote breaker, for all internal faults except three-phase. Loss-of-load, plus a zone-2 timer, also provides a secure and sensitive detection for open-conductor conditions that occur when the line is carrying load.

Dual-Channel Configuration

For those applications where an occasional outage of the channel, in both directions, may be expected (example: microwave fading due to weather), the dual-channel version of charge comparison is suggested. This involves dual transceivers at each terminal and two separate communications links with diverse routing. The channel in use is automatically switched, approximately once per day, to verify integrity. If the channel in use goes into a squelch (loss-of-channel) condition, the switchover occurs immediately. The switchover does <u>not</u> occur during fault conditions, in order to give the outgoing signal on the channel in use the best chance to get through to the remote terminal.

CHANNEL BACKUP, THREE-TERMINAL LINES

Charge comparison for three-terminal lines involves totally separate transmitters/receivers to/from both remote terminals, per Figure 17. Should the bi-directional channel fail (in both directions) between L and R, the charge comparison relay at M remains intact and can sense all internal faults. As soon as a trip signal is developed at M, direct trip messages (without causing reclose blocking) are sent from M to both remote stations.

In summary, the three delta-connected, completely independent TX/RX circuits allow the three bi-directional channels (L/R, L/M and M/R of Figure 17) to effectively back each other up. Of course, this is only valid if the three channels are adequately separated to prevent common-mode failures.

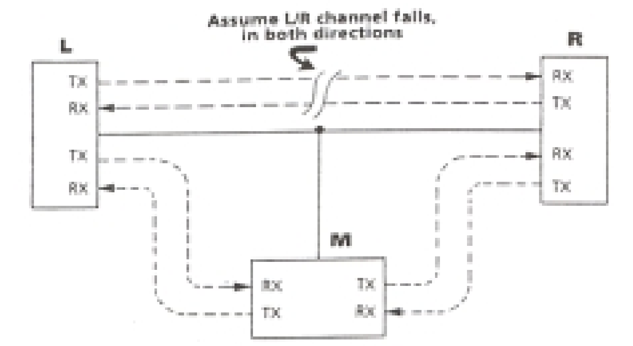

Figure 17. Charge comparison, three-terminal lines

INPUTS/OUTPUTS

The charge comparison system incorporates a flux-cancellation auxiliary current transformer which allows a small iron core transformer to provide isolation and linear transformation, even in the presence of full dc offset and extremely long L/R time constant. The auxiliary current transformer includes a multi-turn test winding that allows testing using pre-recorded waveforms and a low-current playback amplifier.

The breaker trip circuit is monitored by a solid-state dc current sense circuit, based on dc saturation of a magnetic core. This provides indication and seal-in for the breaker trip circuit.

CONCLUSION

Charge comparison largely resolves the three main problem areas of current differential relaying of transmissions lines. Therefore, charge comparison offers a viable alternative to distance-based directional comparison schemes for many transmission line applications.

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Discussion

DOUGLAS C. DAWSON, (Southern California Edison Co., Rosemead, California): I would like to congratulate the authors on an excellently prepared paper and also on their boldness in investigating the limits of a concept that "obviously won't work," like magnitude comparison. The numerous figures and their supporting text show the fine effort which the authors have made to clearly explain their new line relaying concept.

Each protection engineer who reads this paper will probably develop his own viewpoint as to how this new concept works. My own approach is to see it as phase-and-magnitude comparison. The phase information is conveyed by the time-tags and the magnitude information by the time-integral values of the current. The range of phase values for restraint is ±90°, similar to many of the earlier U.S. phase comparison systems. The magnitude information allows for tripping during internal faults characterized by outfeed at one terminal. The combination of the two criteria is the rainbow shape which is similar, at low outfeed levels, to phase comparison with offset keying. However, charge comparison has the advantage that the threshold levels are dynamic, because of the restraint characteristic, instead of the fixed thresholds characteristic of offset keying.

Range of Remote Phase Positions

The reported study on the practical range of remote current phase positions is of particular interest. This subject has been the topic of much discussion in the past for phase-comparison systems, where it is substantially affected by the charging capacitance of the lines under through-fault conditions. Recent U.S. practice has been to provide a restraint region of about ±65° (3 mS) for both segregated and mixed phase-comparison systems. This is a change from prior U.S. systems which used ± 90°. British engineers seem to favor a restraint sector of ± 30-40°, with offset modulation thresholds which give the effect of a larger restraint region at low currents.

These practices seem to be in reasonable agreement with the approximately ±25° shown for through-fault currents in Figure 7 of the paper. Conversely, the charge-comparison relay itself has a restraining range of ±90°. Though this is clearly of benefit in tolerating channel delay compensation errors, it leads one to wonder whether there are any internal faults for which the relay might fail to trip because of this larger restraint range. The authors conclude, based on their study, that such currents cannot exist except for unrealistic conditions. It would be helpful in accepting this conclusion if the authors would indicate the assumptions and parameter ranges used in this study. In particular, it would be helpful to know the range of source-to-line impedances studied, the maximum phase angle between sources, and whether parallel lines and open-conductor faults were included. Also, concerning series compensation, are the 70% and 90% values given as a percentage of the line impedance or of the total impedance between sources? While it is true that lines are seldom compensated in excess of 70%, the capacitor bank reactances are often considerably larger than the impedance of the source behind them which can produce reverse current for a high resistance fault, depending on the fault location.

Zero-sequence Comparison

Concern has often been expressed about phase comparison or current differential schemes using zero-sequence current without some other supervising function. The potential problem is that erroneous ct outputs during through faults not involving ground (phase-to-phase or three-phase faults) could cause misoperation of the protection. Since the measured residual currents, if any, during such faults are entirely error currents, the currents at the two ends have no definite relationship and might be of such magnitude and phase as to cause tripping. My company's experience with zero-sequence phase comparison has not shown this to be a practical problem, at least on HV and EHV lines. It might be a more serious concern on subtransmission lines where through-fault currents may be higher, the quality of the CT's not as good, and faults not involving ground more common. I would appreciate the authors' assessment of this potential problem for the charge-comparison scheme. Would it be practical to add restraint to the zero-sequence comparison when the measured phase current levels are high?

UHS Trip

The description of the UHS (ultra-high-speed) trip feature seems to suggest that it is simply an instantaneous overcurrent function. Such a function would not be satisfactory for many applications on shorter lines. Could the authors clarify how the UHS trip works? Is it applicable to three-terminal lines?

Tapped Loads

The authors correctly point out that it difficult to apply current differential with tapped loads on the protected line. However, many practical applications are possible by de-sensitizing the protection such that it cannot see a load-side fault on the tapped transformer, but can still see all line faults. The same should be true for charge-comparison protection, provided that the sensitivity level is adjustable. The paper indicates only that the pickup level is 0.5 ampere. It would seem that an adjustment for this value would enhance the applicability of the new relay.

Manuscript received February 10, 1992.

H. G. Farley and **G. J. Morgan**, (Public Service Electric & Gas Co., Newark, NJ): We would like to congratulate the authors for a well-written paper on a new and viable concept to current differential relaying for line protection. As described in the paper and a related paper concerning the communications aspect [1], the charge comparison concept is unique and does address some of the disadvantages of traditional current differential relaying.

A disadvantage of current differential relaying, that is not addressed in the paper, concerns protection of two terminal lines with large tapped loads. It is becoming increasingly difficult to operate power systems with clean two or three-terminal transmission lines and lines with large tapped loads are becoming more prevalent. The sensitivity of current differential relaying is such that coordination is difficult and low side faults at the tapped load will, in most cases, result in a loss of the line. Local clearing at the tapped load is desirable and loss of the associated line should be avoided where possible. Numerous schemes have been used to minimize transmission line outages where current differential relaying is applied to lines having large tapped loads. High set fault detectors, time delay, distance relay supervision, and decreased sensitivity are some of the methods that have been used. All of which reduce the effectiveness of the current differential relaying scheme. The authors comments on this concern would be greatly appreciated. In particular with respect to the application of charge comparison current differential relaying concepts.

The foregoing comments are not intended to detract from the concepts presented in this excellent paper but, to emphasize the electric utility concern with protection of transmission lines having large tapped loads, in particular where current differential relaying is to be applied.

Reference

[1] Norman P. Albrect, William C. Fleck, Kenneth J. Fodero, and Robert J. Ince, "Charge Comparison Protection of Transmission Lines—Communications Concepts" IEEE-92WM210-5PWRD.

Manuscript received February 6, 1992.

J. G. Andrichak, G. E. Alexander, M. G. Adamiak, and **R. C. Patterson,** (GE Meter and Control, Malvern, PA): The authors are to be congratulated on a clever use of digital communications in the integration of a new current differential technique. The discussers ask the authors to comment on the following aspects of their paper:

In describing the drawbacks of Phase Comparison relaying, the authors describe "high frequencies" as "poking holes" in the transmitted square waves. Could the authors elaborate on the range of "high frequencies" to which they were referring as well as the relationship to the magnitude of current wherein "holes" would be formed. This appears to be addressed in the charge comparison technique by desensitizing the relay as indicated on page 5.

Could the authors comment on the performance of their relay under severe saturation as caused by large cross feed currents as may be found in a breaker and a half scheme where the ratio of CT cross feed current to line relay current may be as much as 10 to 1 (see Figure 1). Properly designed Directional Comparison schemes will provide blocking for this case.

In their paper, the authors reference the paper "Mica 500 kV Protection" by M. J. Lefrancois and indicate that half-cycle protection is obtainable for all internal faults. The scheme described in the reference obtained high speed operation by using dual systems—one that compared phase on the positive half cycle and one that compared phase on the negative half cycles. Could the authors expand on their variation of this technique as well as the effect on operating time and other performance factors for single phase tripping applications.

It is not clear from the paper how CT saturation and other distortions in the relay currents can be successfully distinguished to prevent false tripping while not compromising speed and dependability on internal faults. For example, on page 7 the authors state that an inhibit circuit is included to prevent false tripping on the "double excursion condition" of Figure 16. How will the relay respond if this "double excursion" is actually an internal evolving fault?

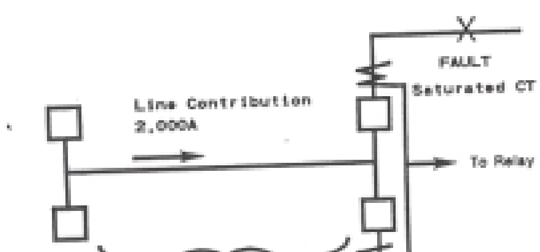


Fig. 1.

SECONDARY IMPEDANCE

LEFT SOURCE	LINE	RIGHT SOURCE
Z1: 1.5 at 85 deg	Z1: 6 at 88 deg	Z1: 1.5 at 85 deg
Z0: 2.5 at 60 deg	Z0: 18.5 at 76 deg	Z0: 1.5 at 88 deg

Fig. 2.

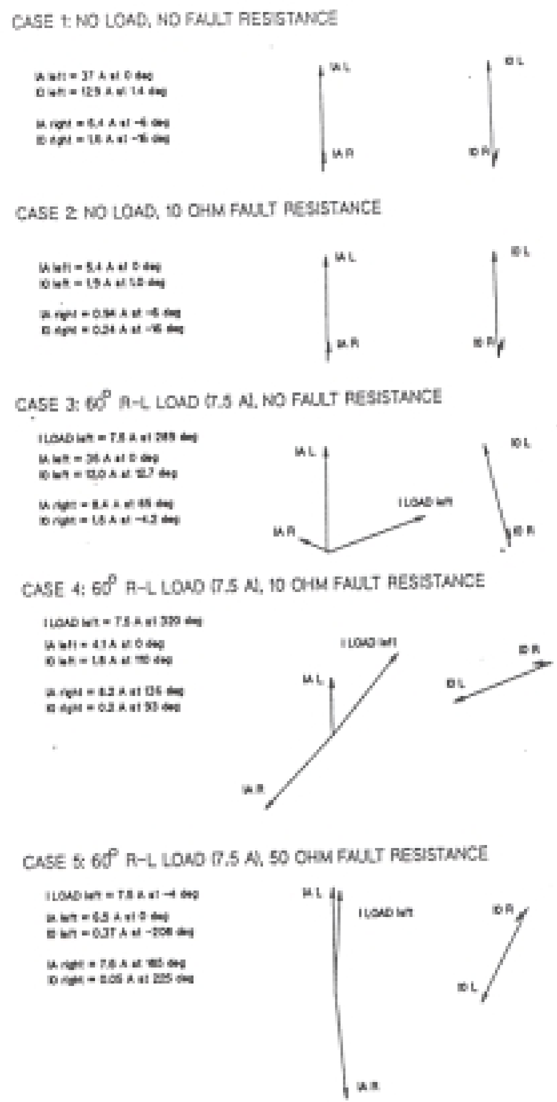


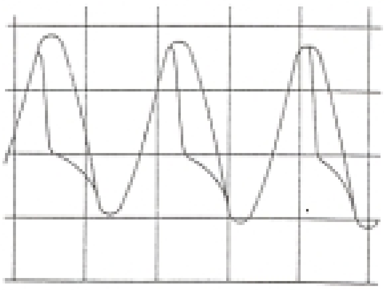
Fig. 3.

The simple system of Figure 2 is used to demonstrate several phase to ground faults for various load and fault impedance conditions. The resulting phase and zero sequence currents are shown in Figure 3. Note that in order to appear similar to the figures in the authors paper, phase A current at the left (IA L) has been chosen as the reference and is always plotted vertically.

In the first paragraph on page 3, the authors state that "the high impedance ground fault current, which is always resistive limited, is essentially in-phase or out-of-phase with the load current on the faulted phase." Case 5, 50 ohm fault resistance and 7.5 ampere load current shows this to be the case. However, Cases 3 & 4, with high load and lower fault resistance show that the angle between the currents at the line ends is highly variable, as is the relative magnitudes of the two currents. In fact, the plots of the currents for these two cases seems to contradict the authors claims relative to Figure 7 as they appear to plot in the area labeled "cannot exist." Since the authors did not include any scaling on their figures, this can not be confirmed. Would the authors care to expand on their figures to include appropriate scaling? We would also appreciate the authors comments on the expected performance of their proposed relay for the conditions of Cases 3, 4, & 5. Note that for Case 5, the zero sequence current at both ends is relatively small. Will the relay be sensitive enough to respond to high resistance faults from sources such as trees and fires under power lines when the phase currents are out of phase?

A. Apostolov, (New York State Electric & Gas Corp., Binghamton, New York): The authors state that they have developed a new transmission line protection technique suitable for protection of two- and three-terminal lines of all lengths and voltage levels. The description of the charge comparison principle sounds like an application of current differential relaying with a current measurement technique (rms value calculation based on instantaneous values measurement) used in many digital current transducers. It would be useful to have the authors comment on the following questions:

What is the effect of CT saturation and harmonics on the relay operation—for example if the saturated half-cycle pulse is less than 6 ms wide?



How does the relay operate for the fault shown in Fig. 1.f of the paper?

If the relay is applied at a short line close to a strong source, where high speed clearing is required, how will the UHS unit distinguish between an internal and external fault?

Will the authors describe the algorithm used for coulombs calculation and coulombs to amperes rms conversion?

W.J. Cheetham (GEC Alsthom Protection & Control Ltd., Stafford, England) :

* CHARGE COMPARISON PROTECTION OF TRANSMISSION LINES—*RELAYING CONCEPTS, Leonard J. Ernst, Walter L. Hinman, David H. Quam, James S. Thorp*
* CHARGE COMPARISON PROTECTION OF TRANSMISSION LINES—*COMMUNICATIONS CONCEPTS, Norman P. Albrecht, William C. Fleck, Kenneth J. Fodero, Robert J. Ince*

I wish to congratulate the authors on producing two very well written papers. I would like to make a few comments on the Measurements and Communications aspects of the new relay.

Polar Diagrams

The paper compares the operating and stability performance of the 'Charge Comparison Protection' with 'Conventional Current Differential' protection.

I found it difficult to make any meaningful comparisons as scales are not included on any of the diagrams.

To give an example, reproducing Fig. 10 in the paper (see Fig. 1):

For conventional current differential schemes $A = 0.5I_L$ $B = 1.5I_L$

What are the corresponding values for the Charge Comparison Protection?

It is theoretically possible to reduce the conventional relay characteristic to the small circle. This is probably not possible for stability reasons but the point is, the diagram does not mean a lot without SCALES.

Sensitivity

Except for high resistance faults, fault current, in general, will not be in phase with Load Current.

As shown on Fig. 2, for the conditions assumed the conventional current differential relay has greater sensitivity.

Although the Charge Comparison Protection probably has greater sensitivity for HR faults, are these not covered by the Zero Sequence Element?

If this is so, why compromise the phase fault settings?

Stability

Turning to the aspect of stability, it would be interesting to have more details on how the zero sequence element is stabilized.

I presume this element is a Biased Element and if so what is the Bias Quantity, the phase fault current or the residual current?

If the residual current is used this could lead to stability problems when used with different current transformers with different saturation characteristics. What tests have been carried out to prove STABILITY?

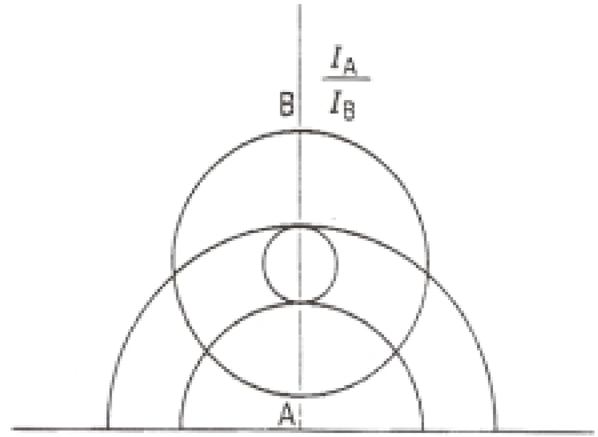


Fig. 1.

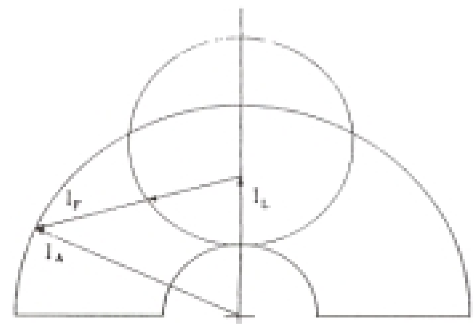


Fig. 2.

To overcome some of the basic problems associated with gap measurement, the protection is provided with a number of other elements, particularly a 'UHS' element set at 2.5 rated current.

This appears to be a simple O/C relay (non-biased), its only criteria for operation being that the current must exceed the setting for 2 ms.

If this is correct, does it not invalidate the bias characteristics shown in Fig. 12 above 2.5 x-rated current?

Communication Channel

Regarding the use of different communication channels, on reading the papers it does seem that some compromises have been made in the design adopted to ensure operation on VF analogue channels.

If only a 56 kB digital channel was adopted then I feel that a better overall solution could have been achieved.

As stated in the paper, a number of 'Additional' elements have been incorporated into the design to overcome the shortfalls of the basic measurement principle adopted under different operating conditions.

My own experience is that the more independent features that are provided the more difficult the coordination between the different elements become.

Could the authors indicate whether they consider the use of Fourier Filters which, of course, filter the DC component and higher frequencies and also provide the Phase Information of the Current Vector. This technique would seem to overcome all the problems encountered by the use of Zero Crossings as identified in the paper.

Finally, I would suggest that the transfer of full Vector Information is essential to achieve protection of three-ended lines under all conditions of load flow and system configuration.

Manuscript received February 7, 1992.

G. D. Rockefeller, (Rockefeller Associate, Inc., Morris Plains, NJ): The authors describe in their companion papers a well-conceived, innovative design concept. I use the word "concept," since they did not report on any system tests.

A key feature is its suitability for 7200 baud channels. A comparable full-differential design requires a 64 kB channel; here the term "full differential" connotes the transmission of magnitude information over a wide dynamic range. What is the bit size of the A/D converter? What happens if an overflow occurs?

The design is described as digital, but the term "microprocessor" is not used, except in relation to the modem. Are multiple processors used and if so what is the division of work?

Would the authors provide the scaling for Figs. 12 and 13 of the Relaying Concepts paper? Page 6, col. 1 of this same paper seems to imply that Fig. 12 transforms precisely to the rainbow shape of Fig. 9. They are not convincing that this is *precisely* so; it appears that a rainbow-*like* shape is produced. Note that Figs. 4 to 10 involve the phase or residual currents at the two stations: Il and Ir; whereas, Fig. 12 depicts the relations between the scalar and arithmetic sums of Il and Ir. Moreover, the Fig. 12 characteristic is not linear.

While the basic concept seems inherently sound, some of the ancillary features (e.g., weak-feed logic) bear scrutiny via system testing. Would the authors expand their description of the weak-feed logic: in particular is nesting required? Is it secure during energization of a long line? What is the cutoff frequency of the anti-aliasing filter?

Would the authors expand their description of the UHS logic?

Fig. 13 shows qualitatively an increased sensitivity. This increase may make the scheme vulnerable to operation due to dissimilar ct saturation during energization of a large power transformer external the line, by virture of a protracted offset current component at a low current level. Have the authors established any ct selection criteria?

Would the authors expand their description of their "flux-cancellation" auxiliar cts and their trip-circuit sensing device.

Manuscript received January 22, 1992.

W. A. Elmore and **R. E. Ray,** (ABB Power T & D Co., Inc., Coral Springs): The authors are to be commended on an interesting variation of a current differential scheme. However, in the very beginning of the paper, it is evident that the authors are comparing their concept which is under development to current differential schemes of fifteen years ago and not to modern microprocessor based systems. Taking their "critical disadvantages one at a time, it is obvious that they are decrying the disadvantages of a by-gone era.

1. "Protection lost if channel fails"—In the modern implementation of the segregated phase comparison system, it has been a simple matter for those equipped and well versed in distance relaying concepts to utilize the capabilities of the microprocessor to revert from the normal pilot phase comparison relaying scheme to a non-pilot two-zone phase and ground distance scheme upon the detection of any channel inadequacy. The concept of bringing voltage to the relay scheme poses no problems since vt's are usually present in the station.
2. "High-capacity channel required, particularly if each phase is protected separately"—Modern digital channel techniques allow a four subsystem (A, B, C phase and ground) scheme to be accommodated at high speed over a single analog or digital voice channel.
3. "Precise channel delay compensation required"—The rather large margins inherent in normal phase comparison allow considerable deviation in square wave alignment for external faults. However, to permit greater error accommodation from other influences such as ct output phase shift differences and line distributed capacitance, continual determination of actual channel delay is effected in any present-day design of phase comparison relaying.

With the three "critical" disadvantages relegated to insignificance, it is evident that the "rainbow" scheme affords nothing that is not achievable by a modern segregated phase comparison system and, indeed, is quite inadequate in terms of its behavior following channel failure.

The authors indicate that the "storage operation" for "charge comparison" occurs only if the half cycle pulse width is 6 ms or more. Does this mean for an offset waveform, that it is quite likely that the process of comparison may be delayed in the beginning for a full cycle if zero crossings were at say 0, 5.9, and 10.7 ms.

It is stated in the paper that "magnitude is measured in terms of ampere-seconds . . . (and) converted to amperes rms equivalent based on a perfect 60 hertz sine wave without offset." Have the authors examined the significance of this in light of the fact that a perfect 60 hertz sine wave is not to be found in the vicinity of a fault near a series capacitor.

The UHS description seems to say that the trip time may be 16 ms plus 4 ms or 20 ms using a voice channel. The industry has come to regard UHS as less than 8 ms overall time and the authors seem to be suggesting a new definition. We are curious as to the reasons dictating the choice of 12 A peak (for 2 ms) as a level at which the charge comparison concept is abandoned. These criteria can be satisfied with a 9.12 A rms (symmetrical) current. Since it is called UHS, does this mean that local tripping is accomplished immediately upon the identification of the 12 A instantaneous value. How does dc offset influence this?

We are flattered by the author's selection of the load-loss trip concept that has been used by the discussers company for approximately four years in a multi-zone distance relaying scheme. We hasten to point out, however, that it is useful for end zone faults cleared by a zone-1 distance relay at one end and seen by a zone-2 distance relay at the other, to accelerate trip at the zone-2 end. The use of a zone-2 timer, driven by overcurrent is a poor substitute for a zone-2 distance scheme utilizing load loss trip. What is the nature of the sequential trip the authors envision for the "rainbow" scheme following channel failure.

Manuscript received February 6, 1992.

CLOSURE

L. J. ERNST, W. L. HINMAN, D. H. QUAM
AND J. S. THORP

The authors would like to thank the discussers for their interesting comments and questions. Several discussions include questions about "UHS". These questions are addressed in the closure to the companion paper (Ref. 1).

With reference to Mr. Rockefeller's first question, the A/D converter is 10 bits. The A/D converter truncates at 63.5 A peak.

Note: All currents in this closure are based on 5-ampere current transformer secondary currents.

Seven microprocessors are used. One microprocessor controls each phase (including residual), one controls the communications, one controls the display and one serves as system supervisor.

Figures C1 and C2, provide the scaling for Figures 12 and 13 of the paper.

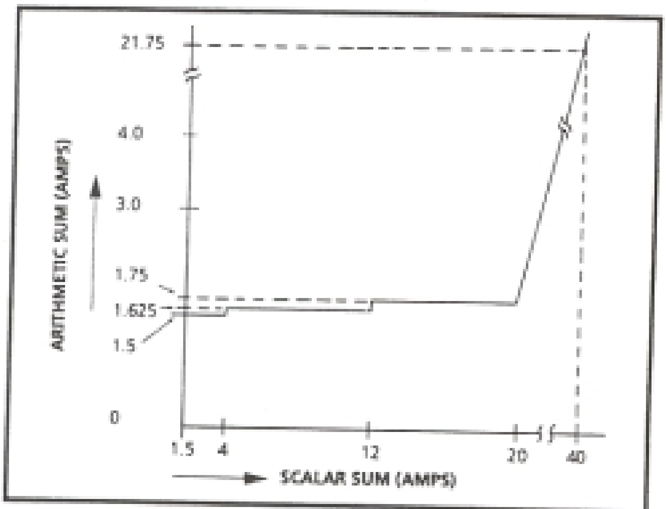


Figure C1. Bias characteristic.

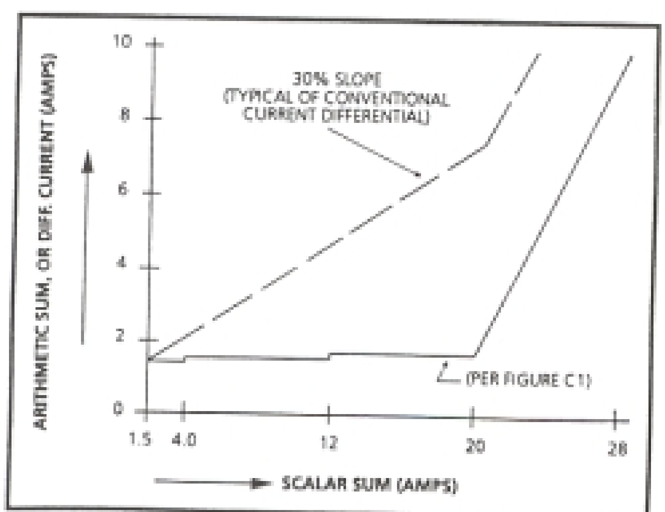


Figure C 2. Bias characteristic, charge comparison vs. conventional current differential.

Figure 12 of the paper does transform precisely to the rainbow shape of Figure 9, if the local current is 2 A through 9.125 A. For example, let the local current be fixed at 5 A rms, at zero degrees. The bias characteristic of Figure C1, shows that when the remote current is at 180°, balance points occur at remote current magnitudes of 6.625 A (SS = 11.625, AS = 1.625) and 3.375 A (SS = 8.375, AS = 1.625). When the remote current is at any other angle between 90° and 270° it will still "nest" with the same local negative half-cycle and produce balance points at the same magnitudes: 6.625 A and 3.375 A. This creates a "perfect" rainbow, per Figure C3.

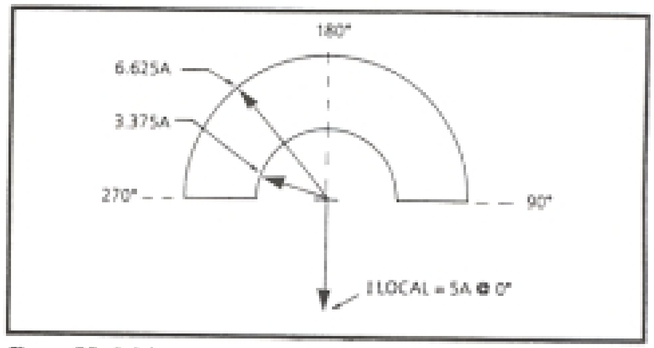


Figure C 3. Rainbow, I local = 5A

Note: In reality the local currents are rounded to the closest 1/8 A and the remote currents are rounded to the closest 1/4 A (to conserve bits required by the communications channel). Therefore, the effective rainbow characteristic departs slightly from that shown in Figure C3.

If the local current is 9-1/4 A, or greater, only the lower half-circle of rainbow applies (example: Figure C7). If the local current is 1/2 A, or greater, and less than 2 A, then the polar diagram characteristic is a different shape, made of half-circles (example: Figure C11b).

The weak feed logic works by integrating the absolute value of current samples over a moving 8-millisecond window called "FCA" (Floating Current Accumulator), without regard to zero-crossings, harmonic content or polarity. Whenever a CCD (Charge Comparison Data) message is received of magnitude 4 amperes or more, the relay looks for an FCA value of 1.5 A equivalent, or less, that occurred in the same real time as the 4 A half-cycle at the transmitter terminal. If a match is found, then the system declares a "WFT" (Weak Feed Trip).

From the above description, it is seen that the weak feed circuit does involve a time matching that is equivalent to the "nesting" process described in the paper. The timing operation that selects the correct FCA has a ±4 ms tolerance for improper channel delay compensation. This is the same tolerance as that of the CCD nesting operation.

The weak feed circuit is secure during the energizing of a long line, since a significant current (4 amperes, or more) of good frequency content (at least 6 ms half-cycle duration) must be received at the open breaker terminal in order to trigger the WFT.

The cut-off frequency (3 dB down) of the anti-aliasing filter is 200 Hz.

If protracted offset may occur at low current levels, it would seem to be appropriate to raise the entire bias characteristic, per the upper curve of Figure C4. This is a user setting. For this condition, the upper curve of Figure C4 appears to be more secure than the upper curve of Figure 13 of the paper.

The main CT's (current transformers) must have the same ratio. They should be of the same type. The charge comparison relay presents a very small burden (0.0015 ohms per phase). Furthermore, the UHS circuit requires only 2 ms of good current to trip for internal faults, and 1/2 ms of good current to correctly block for external faults. Also, the charge comparison itself has high restraint for high current through faults. Even so, good quality main CT's are recommended. C200 would seem appropriate for most ap-

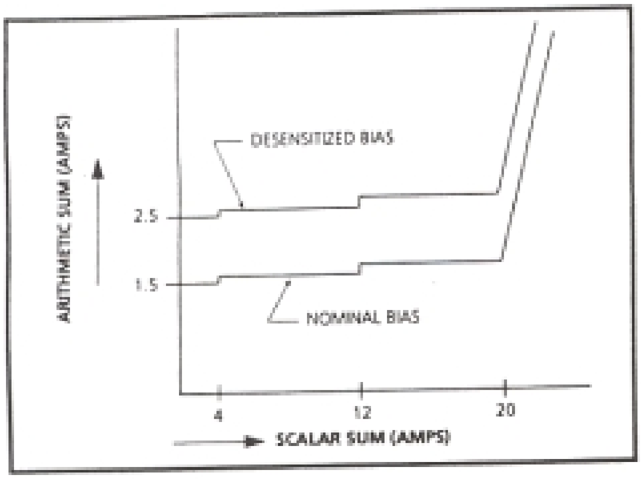


Figure C4. Desensitized bias

plications. Of course, the selection of the CT depends on maximum expected fault current, dc time constant, CT ratio and total connected burden. In making the CT calculations, a conservative approach is suggested when applying charge comparison, or any current differential scheme.

With regard to the main CT's, the major concern is "spill" (i.e., spurious differential) current in the residual circuit for heavy through phase faults and in all circuits for heavy cross-feed currents in double-breaker terminals. These issues are addressed below in response to other discussions.

The "flux-cancellation" Auxiliary Current Transformer (ACT) is a small iron core with secondary circuits that detect small flux levels and inject feedback currents that virtually cancel the flux. This permits the ACT to be completely linear up to 350 A peak, in the presence of full dc offset and very long dc time constants (100 ms or more). Repeated tests with short current bursts of the same polarity dc offset have proven that the ACT serves as an ideal transformer. A patent on the ACT and associated circuitry is pending.

The dc trip-circuit sensing device is a tiny iron core that transforms a high frequency signal. The dc trip-circuit wire passes through this core. Whenever this wire carries 1/2 A dc, or more, the core saturates and interrupts the magnetic coupling of the ac signal. This provides "series trip" target information and seal-in of the auxiliary tripping relay.

With reference to the first comment by Messrs. Elmore and Ray, the authors recommend that distance relay backup, if required, be a package that is separate from the current differential or phase comparison relay. This would provide backup for all parts of the protection, including CT secondary, fused dc circuit, power supply and auxiliary tripping device.

The authors agree that modern digital channel techniques allow A/B/C/G phase comparison over a single voice channel. However, we believe that charge comparison is the first (and only, so far) scheme that performs A/B/C/G current differential, or equivalent, over a single voice channel.

The authors agree that precise channel delay compensation is not required for phase comparison. Page 4 of the paper states that "phase comparison has good tolerance for improper channel delay compensation". Page 1 of the paper says that the requirement for precise channel delay compensation is a "disadvantage of (existing) current differential relaying", not phase comparison relaying.

The authors contend that the "rainbow" concept is superior to phase comparison, with or without offset keying. This is largely because of the ability of rainbow to handle outfeed conditions of all levels. Quoting a discussion of this paper by Mr. D. C. Dawson: "- - - charge comparison has the advantage that the threshold levels are dynamic - - - instead of the fixed thresholds characteristic of offset keying".

Charge comparison, like all other current differential schemes, has numerous other advantages (in addition to handling outfeed) over phase comparison. With reference to current differential protection of transmission lines, Professor Arun Phadke wrote (Ref. 2): "By exchanging actual current signals between various terminals - - - rather than the phase angle information alone as in phase comparison relaying, the resulting system is far more sensitive and accurate". In charge comparison, this extra information enables such functions as "weak feed", "UHS" and variable bias - all of which are dependent on recognition of magnitude, in addition to phase angle.

An offset waveform will tend to have a long second half-cycle, if the first half-cycle is short, as shown in Figure C5. Therefore, we would not expect a full cycle delay due to two consecutive short half-cycles. For severe faults, even the short first half-cycle will often exceed the 12 A peak level for 2 milliseconds, thereby providing UHS tripping during the first half-cycle after the fault.

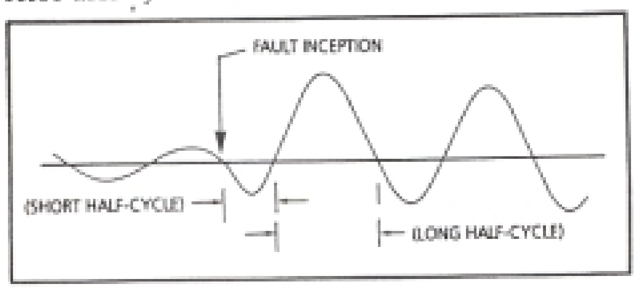


Figure C5. Offset waveform with short first half-cycle

It is true that the conversion from ampere seconds charge to equivalent ampere rms is only accurate for a perfect 60 Hz wave without offset. The authors agree that this conversion is not correct during the off-normal frequencies associated with series capacitors or during the transient interval during a fault. The accuracy of this conversion is not significant, except during relay calibration and measurements, which are all done during the steady-state, or slowly changing conditions. At these times the conversion is accurate. The relay operates on charge comparison, based on the principle of conservation of charge. The only reason for converting the charge to rms current is to allow conventional ammeters to be used and allow description of pick-up levels and settings in terms of amperes instead of coulombs.

With reference to loss-of-load as used in the charge comparison system, this technique provides high-speed sequential tripping if the channel is lost in one direction, but not the other. During an internal fault, the terminal receiving valid communications will trip in high-speed (typically 1-2 cycles) via charge comparison. As soon as the breaker at this terminal opens, the other terminal (receiving invalid or no communications) will trip on loss-of-load, provided there was prefault load current (at least 1.5 amperes) and the fault is not three-phase. A zone-2 timer is not required.

As requested by Mr. Cheetham, Figure C6 recreates Figure 10 of the paper, with scales added. Also shown is the restraint circle of the conventional current differential relay, with the "A" and "B" intercepts as suggested by Mr. Cheetham.

We agree that fault current, except for high resistance ground faults, will usually not be in phase with load current. However, these are high current

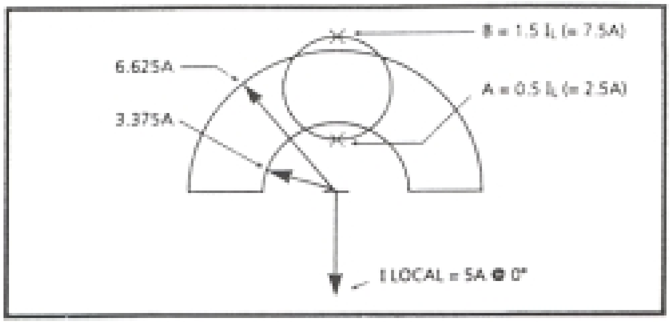


Figure C6. Example of rainbow and circle.

faults because there is no resistance limiting. Therefore, the magnitude of fault current is much greater than the magnitude of load current. All current differential schemes, including charge comparison, have no trouble clearing these high-current faults, which plot well outside the rainbow (or circle).

To illustrate this, let us examine some simple cases. Let us look at the extreme case of a 60° load angle. (A high load angle is the worst case for any current differential scheme, because the high angle increases load current without increasing fault current.)

First, let's consider internal phase faults at the electrical center. (This is a worst-case fault location for charge comparison because fault current infeed magnitudes are the same.) Remote currents will plot in the lower half of the rainbow characteristic. This is because the left-side and right-side currents are more in-phase than out-of-phase, even for the extreme case of the 60° load angle. For example, internal three-phase faults will plot as per Figure C7. An internal BC fault will cause the phase B and phase C currents to plot per Figure C8.

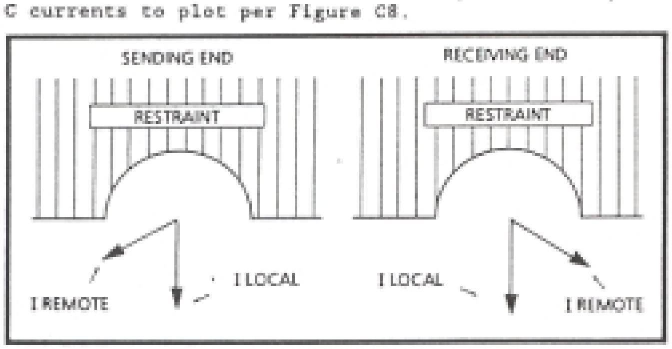


Figure C7. Int. 3-phase fault at electrical center, 60-degree load angle.

Next, let us consider an internal A-G fault at the worst-case location (i.e., the electrical center). Let us assign a Z0/Z1 ratio of 3. This is also a worst-case assumption, since it assumes all the impedance is transmission line impedance. In reality, intermediate ground sources will help make the effective ratio less than 3. The left-side and right-side phase-A and residual currents plot as shown in Figure C9. We are not concerned about the fact that the remote phase-A currents plot close to the rainbow, for three reasons:

* The assumed maximum load angle of 60° is extremely severe. Normal maximum angles are closer to 30°.
* As the fault moves away from the electrical center, the remote current plots further from rainbow.
* As noted by Mr. Cheetham, the charge comparison system includes a $3I_0$ unit, which is unaffected by load current. As shown in Figure C9, the $3I_0$ phasors are essentially in-phase, so they do not plot anywhere near the rainbow.

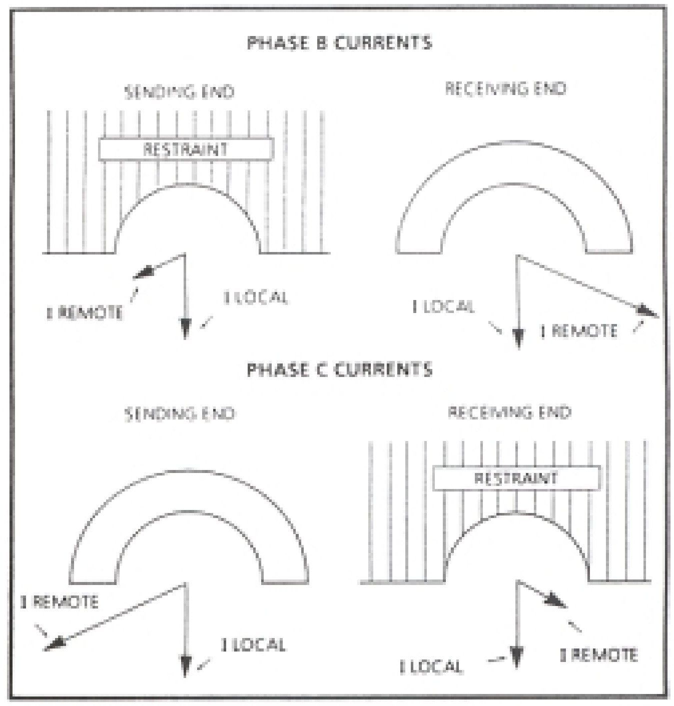


Figure C8. Internal BC fault at electrical center, 60-degree load angle.

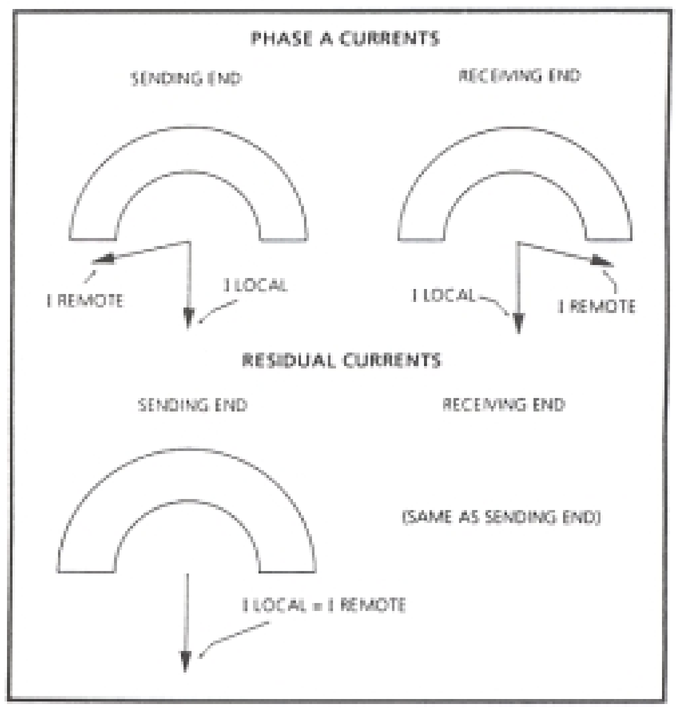


Figure C9. Internal A-G fault at electrical center, 60-degree load angle.

As discussed above, we don't feel the phase fault settings are "compromised". We feel the 90° threshold (i.e., the rainbow ends at ±90° from 0°) gives the optimum combination of sensitivity and security. We want good phase unit sensitivity for ground faults so that the system will be very suitable for single-pole tripping schemes. Therefore, we don't want to rely totally on the zero-sequence unit.

In the present design, the zero sequence element is stabilized by residual current. It is quite true that heavy external phase faults can give rise to spurious residual currents that appear as spill currents. (Mr. Dawson has also pointed this out.) The residual unit of the charge comparison system may require phase current stabilization, for applications with questionable CT performance. A stabilizing resistor in the residual circuit (suggest 1/2 ohm) may also be considered. The best solution is adequately sized main CT's.

Tests to prove stability in the presence of unequal main CT performance during external faults have not yet been performed. We have a high degree of confidence with regard to the possibility of saturation in the main CT's causing malfunction of the relaying system. The reasons for this confidence have been outlined in the closure to Mr. Rockfeller's discussion.

With regard to the discussion by Messrs. Farley and Morgan, the authors agree that tapped loads present a limitation in the application of charge comparison, as well as any current differential scheme. We believe that high-set fault detectors, time delay or distance relay supervision are not desirable solutions to this problem. We believe "decreased sensitivity" is the most effective way to apply charge comparison to tapped lines. Quoting from the discussion from Mr. Dawson: "- - many practical applications are possible by desensitizing the protection such that it cannot see a load-side fault on the tapped transformer, but can still see all line faults". Fortunately, many tapped loads use delta-wye transformer banks, so the $3I_0$ unit does not have to be desensitized. The charge comparison system has provisions for raising the bias level of the phase units without affecting ground fault (residual) sensitivity.

With reference to the discussion by Mr. Dawson, the authors view the reduced (i.e., less than 90^o) restraint region of recent phase comparison schemes (USA and international) as an effort to improve the coverage of marginal internal faults (i.e., high resistance ground faults). Reducing the coincidence timer can allow phase comparison to detect more high resistance ground faults - but not all. It is always possible to place an internal high resistance ground fault that produces only magnitude differences with no phase angle difference at all. The desire to cover more and more high resistance internal ground faults with phase comparison has led to these reduced coincidence timer settings. This has improved internal fault coverage, but has directly reduced the tolerance for improper channel delay compensation during through current conditions. This practice has also reduced security for line charging differential current which has a phase-shift effect on external ground faults which are resistance limited.

In our study of the outer regions of rainbow, the range of source to line impedance ratios was approximately 1 : 10 to 10 : 1. The maximum load angle was assumed to be approximately 30^o, but some studies were made of angles as high as 60^o. Parallel lines were included. Open conductors with short-circuits on one or both sides of the open were considered. Open conductors without short-circuits are handled by the loss-of-load technique, plus a zone two timer. This requires some prefault load or the condition cannot be detected electrically. The 70% and 90% values of series compensation are with reference to the total through impedance (equivalent source to equivalent source). Whenever the source impedance is net capacitive, we agree that there is an outfeed condition, which is a condition for which the rainbow characteristic provides great strength.

We understand Mr. Dawson's concern about spurious zero sequence comparison due to spill currents through the residual circuit. This is discussed in our closure to Mr. Cheetham's comments. Better CT's or stabilizing resistors in the residual circuits are suggested.

The authors appreciate Mr. Dawson's comments regarding tapped load applications. This is discussed above with reference to the comments by Messrs. Farley and Morgan. As previously explained, we recommend adjusting the bias level as the best means to address this issue. The pick-up level of 0.5 amperes referred to by Mr. Dawson is actually the minimum current to store or send charge comparison data, not the bias level of the system, which relates to net differential current (the arithmetic sum of local and remote currents).

The discussion by Mr. Apostolov includes a figure that shows a typical saturated CT secondary waveform. It is observed that the early part of each half-cycle has a "good" output, for at least a short peak. This peak is, of course, of very high magnitude. This magnitude exceeds the 12 A peak requirement of UHS. As will be clear after reading the description of UHS in the closure to the second paper (Ref. 1), UHS will correctly trip for internal faults and correctly block for external faults for the waveform presented by Mr. Apostolov. The charge comparison function, itself, should be secure because of the sharply rising bias level at high currents.

The "less than 6 ms wide" question posed by Mr. Apostolov is addressed, in part, in the preceding paragraph. For internal faults, the UHS (described later) will provide tripping, even though the charge comparison itself is inhibited (since the pulse duration is less than 6 ms). For external faults, the UHS will correctly block (as described later) and the charge comparison itself is inhibited.

Figure 1.f of the paper depicts an internal fault on a three-terminal line, with outfeed at the local terminal. The two remote currents send charge comparison data words at approximately the same real time (within 3 ms of each other). When received, the magnitudes contained in these two words are added, using a formula that takes phase angle difference into account. This total current is then assigned a "composite received time-tag". From there on, the "composite" received current (effectively a phasor sum of the two remotes) is treated just as if it were the single remote current on a two-terminal line application. The rainbow still applies, so outfeed is no problem.

Note: Hardware and overall software provisions for three-terminal applications have been designed. The software is in the planning stage, at this time.

The charge calculation is made by adding each instantaneous sample of current over the half-cycle interval, as determined by start and finished time-tags. This area is actually in "millicoulomb" units. The conversion from millicoulombs to amperes rms was determined experimentally, and verified by theory, to be simply a matter of dividing by 15.

With reference to the first question by Messrs. Andrichak, Alexander, Adamiak and Patterson, the "high frequencies" that can "poke holes" in the phase comparison square waves are probably in the region of 200-300 Hz. These high frequencies are illustrated, in a very general way, in Figure 14 of the paper. Since these high frequencies tend to inhibit tripping, the concern here is dependability, not security. To improve dependability, charge comparison incorporates a weak feed circuit, described previously with reference to the discussion by Mr. Rockfeller.

The authors agree that large cross-feed currents in double-breaker terminals can create spill currents in the differential circuits, phase and ground. This could create a security hazard. We recommend better main CT's or stabilizing resistors (suggest 1/2 ohm) in the differential circuit of each phase and ground as the best solution to this problem.

The techniques described in the conference paper by M. J. Lefrancois (Ref. 19 of the paper) are

rents through the residual circuit. This is discussed in our closure to Mr. Cheetham's comments. Better CT's or stabilizing resistors in the residual circuits
as the best solution to this problem.
The techniques described in the conference paper by M. J. Lefrancois (Ref. 19 of the paper) are

addressed in the closure to the companion paper (Ref. 1).

Comments on CT saturation and its effect on security/speed/dependability have been presented above in the closure to the discussion by Mr. Rockefeller.

The authors agree that an internal evolving fault can appear as a "double excursion" and can cause an undesirable trip inhibit. This can add an extra one-cycle (worst-case) to the trip times. The authors are not concerned about this for two reasons:

* The algorithm that detects double excursions is very selective. In fact, in many thousands of laboratory tests we have not experienced a single undesirable double-excursion inhibit operation.
* If an inhibit signal should occur during an internal fault, it only temporarily blocks charge comparison tripping. It does not affect "UHS" tripping, at all. Therefore, high current internal faults (the only ones that actually require high speed clearing) will not be delayed.

The authors agree that for low or moderate resistance ground faults the angle between fault current and load current can become quite large, as in Cases 3 and 4 of this discussion. The authors have stated that only marginal internal faults (the so-called "High Resistance Ground Fault"), as illustrated in Case 5, create the in-phase (near 0° or 180°) relation between fault current and load current.

Case 3 plots relative to rainbow as shown in Figure C10. Case 4 plots as shown in Figures C11a and C11b. It is observed that in neither case do the remote currents plot near the rainbow, or near the "cannot exist" region of Figure 7 of the paper.

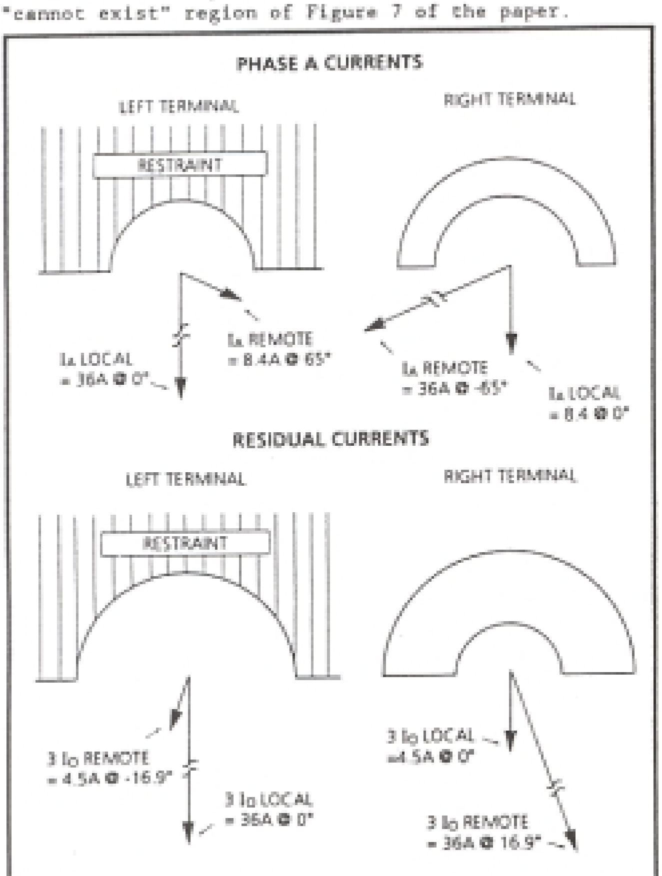


Figure C10. I_A and $3 I_0$, "case 3".

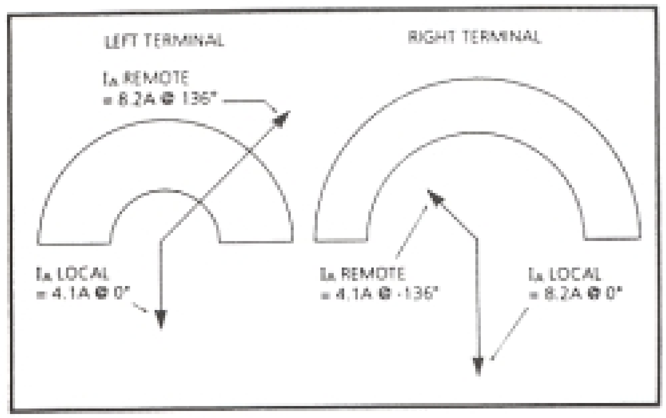


Figure C11a. I_A, "case 4".

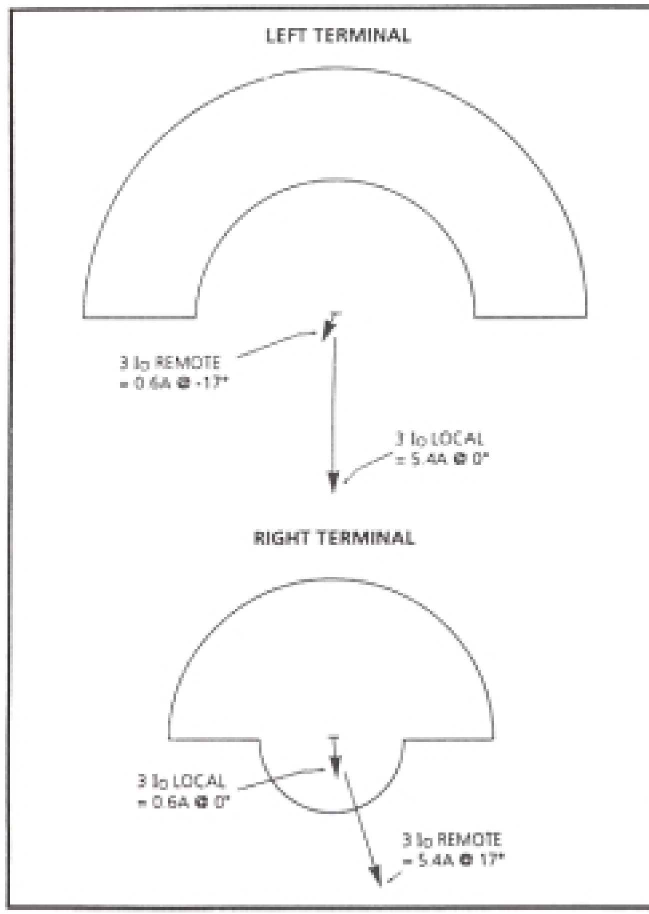


Figure C11b. $3 I_0$, "case 4".

Case 5 does plot inside the rainbow, per Figure C12. Therefore, the charge comparison system fails to trip for this condition. Total fault current is 1.2 A (24% of rated current). This is less than the total fault current sensitivity of charge comparison, which is 1.5 A (30% of rated current). Therefore, the fault resistance of Case 5 exceeds the sensitivity margin of the relaying system. The authors believe that the sensitivity of charge comparison (equivalent to 300 ohms primary fault resistance for a 345 kV line with 2000/5 CT's) will enable the system to respond to many high resistance ground faults as caused by trees and fires under the power lines.

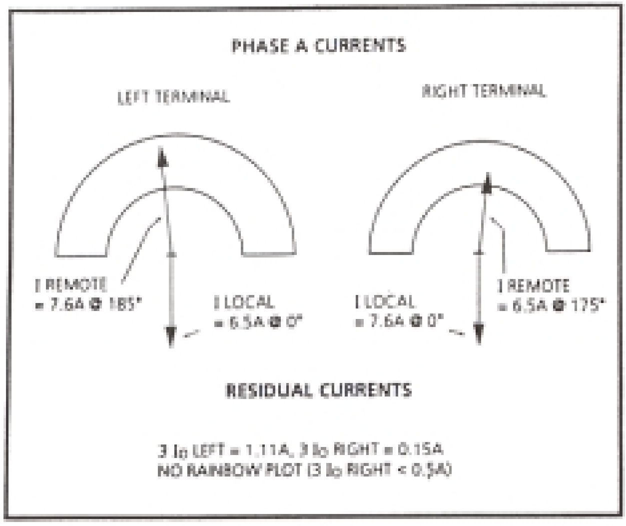


Figure C 12. I_A and 3 I_0, "case 5".

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Manuscript received April 20, 1992.

CHARGE COMPARISON PROTECTION OF TRANSMISSION LINES - COMMUNICATIONS CONCEPTS

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Abstract - Charge comparison is a new transmission line protection system. It compares local and remote quantities of charge, using a bi-directional communications channel. Charge comparison is a form of current differential relaying. Traditional current differential relaying schemes have three critical communications-related problems: protection lost if the channel fails, large channel capacity required, and precise channel delay compensation required. In large measure, charge comparison overcomes these three communications-related problems.

Keywords - Charge comparison, Current differential relaying, Transmission line protection, Digital communications.

INTRODUCTION

Charge comparison is a new digital protection system that combines relaying and communications. The relaying concepts and an overview of some of the communications concepts are presented in a related paper [1]. The communications concepts are described in more detail in the paper which follows.

TRIPPING INSTEAD OF BLOCKING

The most fundamental communications-related decision in the development of charge comparison was the choice of a tripping scheme instead of a blocking scheme. A "tripping" scheme is defined as one that requires the receipt of a bona-fide tripping signal via the communications channel before tripping is allowed. A "blocking" scheme is defined as one that allows tripping in the absence of a received signal. A blocking scheme has the advantage for weak/zero infeed conditions and open breaker conditions (i.e., switch-into-fault). In the absence of a signal from the weak infeed or open breaker terminal, a blocking scheme allows the strong infeed terminal to trip. Tripping schemes require special techniques (echo signaling/open breaker signaling/ etc.) to enable tripping for these conditions. On the other hand, the tripping schemes are inherently more secure. They don't allow tripping during corrupted channel or loss-of-channel conditions.

Early in the development of charge comparison, the decision was made to use a tripping philosophy. Charge comparison makes a new trip attempt every half-cycle. Therefore, during impaired channel conditions, a new opportunity to trip occurs as soon as the channel problem clears.

92 WM 210-5 PWRD A paper recommended and approved by the IEEE Power System Relaying Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1992 Winter Meeting, New York, New York, January 26 - 30, 1992. Manuscript submitted July 15, 1991; made available for printing December 10, 1991.

In the presence of impulse channel noise, the trade-off is:

* A tripping scheme may have slow trips during internal faults.
* A blocking scheme may have false trips during external faults.

To assure good security, charge comparison uses the tripping philosophy and accepts the possibility of slow trips during impulse channel noise conditions. As will be discussed later in this paper, the selection of a tripping scheme, with its inherent security, plays an important role in allowing charge comparison to take advantage of the reliability enhancement offered by parallel-redundant communications.

COMMUNICATIONS MEDIA SUITABLE FOR CHARGE COMPARISON

Since charge comparison uses a tripping philosophy (see preceding section), it is not suitable for use over power line carrier. Internal faults can severely attenuate the carrier signal. This means that power line carrier schemes require a blocking (or unblocking) mode of operation, which is contrary to the tripping philosophy of charge comparison.

Also, charge comparison is not intended for use over a metallic pilot wire (i.e., twisted pair of copper wires between relaying terminals). Reasons:

* In many cases, difficult to obtain copper pairs.
* Induction from fault currents on the power line creating interference in the communications over the metallic pair.
* Ground potential rise, due to difference in station ground potentials during ground faults.

Charge comparison is designed to work with all other teleprotection media:

* Analog voice circuits over leased telephone lines.
* Analog voice circuits over microwave.
* Wide-band (56/64 Kbps) digital channels.
* Fiber Optics.

When working over analog voice circuits, charge comparison incorporates a 7200 bps modem and line coupling transformer. The wide-band digital charge comparison system includes a RS-449 interface, suitable for connection to a T-1 channel bank. The fiber optic charge comparison system includes optical transmitter and receiver equipment, suitable for connection to multimode or single-mode fiber.

THE THREE CRITICAL PROBLEMS OF TRADITIONAL CURRENT DIFFERENTIAL RELAYING SYSTEMS

Reference [1] defines the three critical problems of traditional current differential relaying systems for transmission line protection as:

1. Protection lost if channel fails.
2. Large communications capacity required.
3. Precise channel delay compensation required.

These problems all involve the communications channel. The remainder of this paper will describe in some detail the communications concepts used in charge comparison to resolve these three critical problems.

PROBLEM #1: PROTECTION LOST IF CHANNEL FAILS

This is the most critical problem of any current differential scheme for transmission line protection - and the most difficult one to solve. All current differential schemes compare local current with remote current (or with the sum of both remote currents for three-terminals lines). Therefore, if the communications channel fails there is no knowledge of the remote current, and the relaying scheme cannot operate.

Note: At the time of the writing of this paper, the development planning for charge comparison of three-terminal lines has been done, but the actual hardware and software designs have not been accomplished. Therefore, any references in this paper to three-terminal line protection are purely conceptual.

In general, there are only two ways to provide protection during channel failure:

* Incorporate non-pilot backup.
* Use redundant channels.

Non-Pilot Backup

Current differential schemes operate from current-only. These schemes can readily provide overcurrent backup (with or without time delay), but this form of protection is considered to be relatively ineffective (with regard to selectivity, sensitivity, ease of setting, etc.) when compared to distance relaying. In the development of charge comparison, one approach would have been to build a distance backup scheme into the system. However, incorporating distance backup in the charge comparison relay would have introduced all the problems associated with distance relaying, as outlined in reference [1], including: ferroresonance and transient response problems associated with potential sources, loss-of-potential and low-potential problems, effect of mutual induction on ground distance relay reach, voltage reversals on series compensated lines, blocking requirements during system swings, in-feed on three-terminal lines, etc.

In order to avoid the problems referred to above, it was decided to use only overcurrent functions for the non-pilot backup built into the charge comparison system. This would mean that ac potential would not have to be connected to the relay, thus eliminating the problems associated with ac potential supplies.

Overcurrent Backup

Charge comparison has three overcurrent backup circuits:

* High-set direct trip.
* Switch-into-fault.
* Loss-of-load.

The high-set direct trip is based on overcurrent settings that are entirely independent of the charge comparison current thresholds. The direct trip has separate phase and ground settings, up to 32 ampere rms equivalent (based on 5 ampere current transformers).

The switch-into-fault circuit involves a medium-set overcurrent element (phase setting is above maximum load and ground setting is above maximum residual unbalance) that is allowed to operate for a brief time after breaker closure.

The loss-of-load circuit senses the clearing of the remote breaker during internal faults, except for 3-phase faults. This circuit is described in [1]. The loss-of-load circuit plays an important supporting role in the channel redundancy concepts of charge comparison when applied to two-terminal lines. This role will be described in the next section of this paper.

Redundant Channels

Redundant channels provide protection during primary channel failure by operating in a continuous parallel mode, or by being switched into service in case of failure of the primary channel. Redundant channels improve dependability, but actually degrade security by providing additional opportunities for overtrip. Therefore, redundant channels can improve overall reliability only if they, and the primary channels, are inherently secure in their mode of operation. Charge comparison employs several techniques to ensure this inherent security.

Security Measures

* Charge comparison uses a tripping philosophy instead of a blocking philosophy.
* Each word contains CRC (Cyclical Redundancy Check) coding.
* Fault detectors supervise all charge comparison trips. The fault detectors operate by sensing high current levels or changes in currents.
* Direct trips require reception of two trip messages in a row.
* Strict framing rules prevent false-framing. While receiving synchronous data, each frame bit is tested and, if corrupt, the entire word is discarded, thereby enhancing security.
* "Scrambling" the data also improves security. Every other bit of the information portion of the word is inverted. This breaks up some patterns that could otherwise fool the CRC and framing rules.

CRC Coding

This is a powerful error-detecting code used in digital communications. Charge comparison uses a CRC format and word length that have established an excellent field history in another teleprotection system:

Framing:	1 bit
Information:	8 bits
CRC:	6 bits
Total Word Length:	15 bits

This format catches all 1-bit, 2-bit and 3-bit errors, per word, and most errors of 4-bit and higher. Squelch (alarm and trip-blocking) occurs when many words are rejected. To come out of squelch requires a certain number of good words in a row. CRC and squelch together build a strong security shield for the communications used in charge comparison.

Channel Redundancy, 2-Terminal Line Applications, Single Channel

This arrangement includes a 4-wire (or 2-fiber) channel, with separate transmitter and receiver circuits, per Figure 1.

If the L to R and R to L circuits (or fibers) can be separated, then it is reasonable to expect failed channel circuits in one direction and not the other. If this occurs during an internal fault (see Figure 1), then terminal L can trip at high speed on charge comparison and terminal R can trip sequentially (after breaker L opens) on loss-of-load, assuming that there is pre-fault load current and the fault is not three-phase.

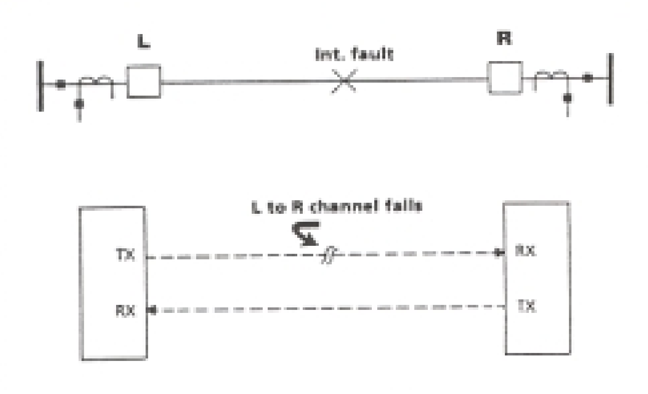

Figure 1. Two-terminal line, single channel

Lending some credence to the above hypothesis regarding channel failure in only one direction are field test results to be reported later in this paper.

In summary, the separation of the outgoing and return circuits of a 4-wire (or 2-fiber) channel effectively simulates the operation of a parallel-redundant channel configuration.

Channel Redundancy, 2-Terminal Line Applications, Dual Channel

If the 4-wire (or 2-fiber) channel is subject to occasional outages in both directions (for example, microwave fading due to weather), a dual channel arrangement is suggested. This provides two totally separate TX and RX pairs at each terminal, and requires separate communications paths (i.e., diverse routing), per Figure 2.

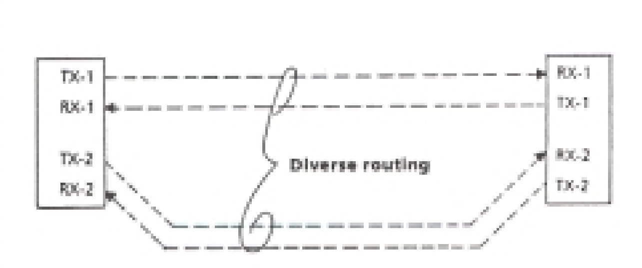

Figure 2. Two-terminal line, dual channel

The charge comparison relay switches channels approximately once a day. The new channel must be re-framed, which requires six words (approximately 12 ms at 7200 bps). If the new channel cannot be re-framed (indicating a bad channel), then the relay switches back to the original channel.

If the channel in use is lost (as indicated by squelch), then the relay switches to the alternate channel. This switchover is not allowed during a fault. Reason: the re-framing of the new channel involves loss of both transmitters for 12 ms, which interferes with the chance to trip the remote breaker. It is felt that the separation of the transmit and receive circuits on the primary and alternate channels gives the required channel redundancy to take care of corrupted channels coincident with an internal fault.

Channel Redundancy, 3-Terminal Line Applications

Charge comparison on 3-terminal lines includes double sets of TX/RX transceiver equipment, per Figure 3.

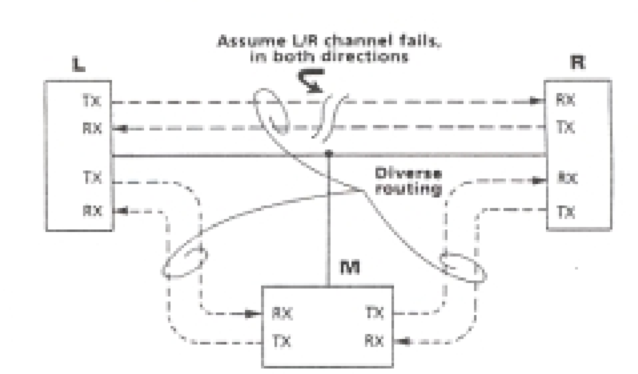

Figure 3. Channel redundancy, three-terminal line

The three delta-connected communications circuits shown in Figure 3 effectively back each other up. Referring to Figure 3, should an internal fault occur and the channel between L and R fails, in one or both directions, the protection at M is still intact and charge comparison tripping takes place at M. As soon as a trip signal is asserted at M, direct trip CCT-U messages from M to L and from M to R command breaker trips at both these stations. The CCT-U message has all the security of the direct transfer trip message, but does not block reclosing.

Once again, the 3-terminal line channel redundancy is dependent on channel separation, including route diversity. In this case, the L/R, L/M and M/R 4-wire (or 2-fiber) channels should be separated from each other as much as possible, in order to minimize common mode failures.

Summary of Protection During Loss-of-Channel

Charge comparison overcomes the number one problem of conventional current differential relays, namely failure of protection whenever the channel fails, only to the extent that the various communications circuits can be separated from each other, to minimize common mode failures. If this separation cannot be achieved, then the backup to charge comparison, in the event of channel failure, must come from some other protection. (The overcurrent direct trip protection built into the charge comparison relay is not considered to be bona-fide back-up.) If this channel separation can be achieved, then charge comparison has successfully resolved critical problem number 1.

PROBLEM #2: LARGE CHANNEL CAPACITY REQUIRED

Up to now, per-phase current differential systems [2] have required a wide-band channel capacity (one voice band per phase for FM schemes, or 56 kbps for digital schemes). In developing charge comparison, the goal was to protect each phase and ground separately, using only a single 4-wire voice grade channel. Of course, if a wide-band channel were available, this could be used.

Another goal was to send numerous auxiliary messages, in addition to the charge comparison messages. These auxiliary messages include Direct Transfer Trip, Ultra-High-Speed, Weak Feed Trip, Open Breaker, etc.

It was clear that only a microcomputer-controlled digital communications system could meet these goals. This meant that a modem would have to be used to provide digital communications whenever the channel was an analog voice grade circuit. For simplicity of modulation scheme and best bit error rate for a given signal-to-noise ratio, the lowest bit rate modem that could handle the traffic was selected: 7200 bps.

Analog Voice Channels vs. Wide-Band Digital Channels

Since charge comparison is intended for use over both voice grade and wide-band channels, two different designs would seem to be appropriate. One design would be optimized for 7.2 kbps, the other design would be optimized for 56/64 kbps. Instead, a single design approach, compatible with both media, was selected. Voice channels are expected to predominate through the mid 1990's, with wide-band digital taking over by the year 2000. A common design approach would accommodate simple field retrofits from voice to wide-band, whenever the wide-band channels become available.

This single-approach concept dictates that the design focus on the worst-case: the 7200 bps modem. Whenever a wide-band channel (56/64 kbps) is used, each word is repeated three times and the receiver uses two-of-three voting logic. This uses the extra channel capacity to enhance both security and dependability, while keeping the design of the relay the same.

By focusing on the 7.2K modem, the original fear was that the design for the higher bit rates would be compromised. This fear is unfounded. A short word length and a delay-compensation-tolerant design (both of which are required for 7.2K applications) also greatly enhance performance for the high bit-rate channels. Reasons:

* The short words (15 bits, as described earlier) have a better chance of getting through in the presence of impulse noise hits.
* The short word length allows 2-of-3 voting, previously described.
* By tolerating a large error in channel delay compensation (described later), charge comparison may be applied to switched wide-band networks where a change in channel delay may occur when the signal path is re-routed.

Reducing the Charge Comparison Required Communications Throughput by 50%

Reference [1] explains that charge comparison information is sent only once per cycle, per phase/ground. Each phase sends only positive half-cycle information and "ground" (i.e., residual) sends only negative half-cycle information. This technique reduces the required throughput by 50%, when compared with sending information on both half-cycles as is done by conventional per-phase current differential schemes. This technique provides tripping on each half-cycle for all internal faults. Therefore, there is no sensitivity or speed penalty associated with this concept.

The authors believe that the creator and first user of this technique was British Columbia Hydro & Power Authority in the mid 1970's. B. C. Hydro reported the use of this concept in the application of segregated phase comparison on the Mica 500 kV System [3].

Communications Message Structure

Reference [1] explains that the basic charge comparison concept greatly reduces the communication throughput required, when compared to conventional per-phase current differential schemes that must send a complete replica of the phasor of each phase current (and ground, if included). Also, as previously explained, the B. C. Hydro concept reduces the required charge comparison throughput by 50%. On the other hand, it has been pointed out that there are a lot of auxiliary messages that should be sent, in addition to the charge comparison information. In order to squeeze all this information into a 7200 bps channel, a special message structure was devised that uses:

* Variable ratio of address bits and data bits.
* Pre-set priorities to determine the order of message transmission.

Varying Address/Data Ratio

This technique reduces the required channel capacity for the expected mix of traffic. The messages that have heavy data content and high frequency of transmission (example: Charge Comparison Data) are assigned a minimal number of address bits, leaving a lot of room for data. At the other extreme, messages that occur infrequently or require very little data content (example: Ping-Pong Initiate) are assigned many address bits and relatively few, if any, data bits. Figure 4 shows the varying ratio of data/address in the different messages. The shaded bits are data, unshaded are address.

This technique is very inefficient (requires too many total address bits) if the different messages must be treated in a random fashion. However, if it is known that the traffic mix is skewed, with some high-priority, heavy-data messages appearing more often than some low-priority, low-data messages, then this varying address/data ratio technique is very efficient.

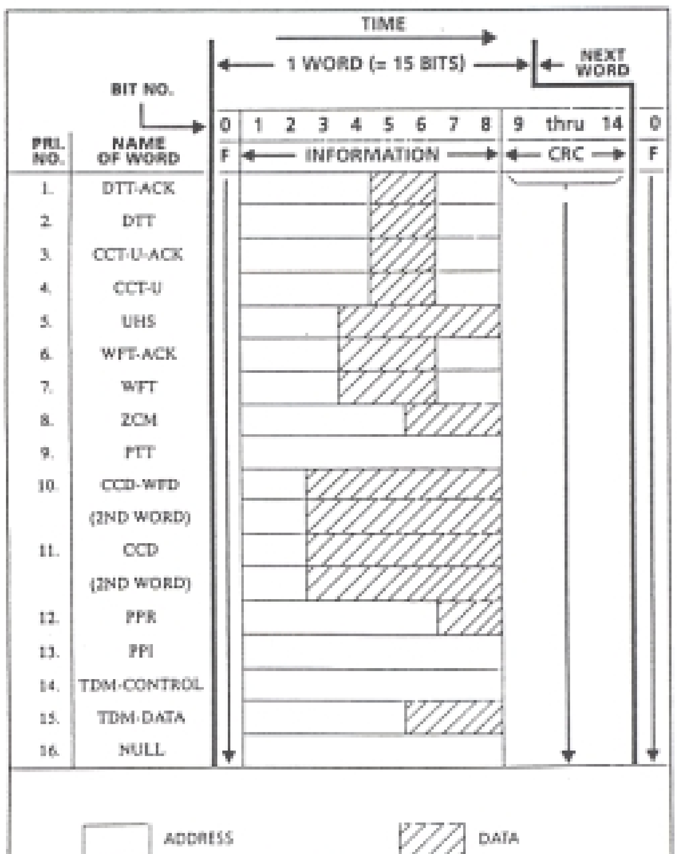

Figure 4. Charge comparison communications message structure

Priority of Messages

Each message is placed in the transmitter queue and waits to be sent. While waiting, it competes for first place in the queue, based on priority. The priority order is shown in Figure 4. Some messages are real-time: Charge Comparison Data, UHS, and Ping-Pong Response. These messages keep track of how long they wait in the queue, and this timing information is included in the data contained in the communications message, when it is finally sent.

One important rule: regardless of the priority of a message waiting in the queue, it never interrupts a message that has started transmission. In particular, a two-word message (CCD, UHS, PTT) is never interrupted after just one word.

Note - CCD and CCD-WFD (Charge Comparison Data - With Fault Detector) consist of a first word and a second word, each one different. UHS (Ultra-High-Speed) and PTT (Permissive Transfer Trip) are always sent in two-word messages, both words the same. (This is done for enchanced dependability - the receiver operates on the receipt of a single UHS or PTT word.)

Acknowledge Protocol

The trip messages (Direct Transfer Trip, Charge Comparison Trip - Ultimate and Weak Feed Trip) are sent continuously until acknowledged. The acknowledge is also sent continuously. For security, two-straight trip/acknowledge words must be received. The terminal receiving direct trip stops sending acknowledge when a different (not the original direct trip) valid word is received. This protocol gives high security and dependability, and also frees the channel quickly, so it can return to other messages. This quick release of the channel can provide useful targeting information for direct trip faults that are inside the zone of charge comparison protection, such as line-connected shunt reactor faults, per Figure 5.

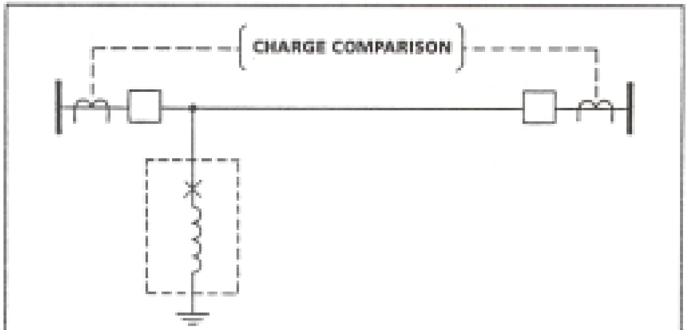

Figure 5. Shunt reactor fault within zone of charge comparison

Summary of Communications Message Structure Philosophy

The governing philosophy is to send many different short messages, all competing in the queue, all with different priorities, and all with different address/data ratios. This concept maximizes the throughput of important messages and also maximizes the chance of getting the important words through to the remote terminal(s).

Contention and Slippage in the Queue

At 7200 bps, there will be occasions when severe time slippage occurs in the queue. For example, during a heavy two-phase-to-ground fault, with load current above 1/2 ampere, seven two-word messages (four CCD and three UHS) will try to go out every cycle - in a time space that can only handle four two-word messages. After four or five messages have been sent, the slippage time will exceed the capacity of the queuing time in the CCD and UHS messages. Whenever this happens, the message is dropped from the queue.

At high bit rates, the slippage is much smaller. There may be contention, causing some slippage, but it is not cumulative as it is at 7200 bps. Each word is repeated three times (equivalent to 21 two-word messages per cycle for the case previously cited). However, the channel capacity is roughly 8 times greater (equivalent to approximately 32 two-word messages per cycle). Therefore, the 56 kbps channel is only utilized at roughly 2/3rds of capacity for this maximum throughput condition.

PROBLEM #3:
PRECISE CHANNEL DELAY COMPENSATION REQUIRED

The rainbow shape of the charge comparison polar diagram characteristic essentially solves this problem [1]. The basic operation of charge comparison achieves a rainbow shape by sending charge information only at the completion of the positive half-cycle of phase current (negative for ground current). The received message is "nested" with the appropriate local half-cycle. This nesting operation is very tolerant of improper channel delay compensation: up to ±4 ms error is allowed.

Although charge comparison is very tolerant of incorrect channel delay compensation, accurate compensation during nominal conditions is desirable. The compensation automatically changes as the channel delay changes - but this update does not occur instantly. Accurate nominal compensation allows the system to work correctly during the interval after a sudden change in channel delay time and before a new measurement can be made and corrected compensation implemented.

Charge comparison uses two channel delay measurement techniques: "Ping-Pong" (round trip delay measurement) and "DML" (delay measurement, based on load current).

Ping-Pong Measurement

Approximately every second each station transmits a "PPI" (Ping-Pong Initiate) message and starts a clock. As soon as PPI is received, the remote station puts a "PPR" (Ping-Pong Response) message in its transmitter queue. If there is nothing of higher priority waiting in the queue, then PPR will be transmitted as soon as the message presently being sent is finished. The remote station keeps track of how long PPR has to wait, and this queuing time is included in the PPR message. The queuing time is then subtracted from the total clock time at the initiating terminal to get actual round-trip transit time, per Figure 6. The charge comparison system uses one-half the round-trip transit time as the assumed channel delay time, in each direction. The same technique is used on three-terminal lines, with a separate measurement made on each delta-connected leg (L/R, L/M and M/R of Figure 3).

Delay Measurement - Load

The Ping-Pong measurement provides an accurate channel delay time only if the outgoing and return channel times are the same. If these times differ significantly, then an error is introduced. Charge comparison incorporates an alternate measurement technique that is not subject to this error: "DML" (Delay Measurement-Load).

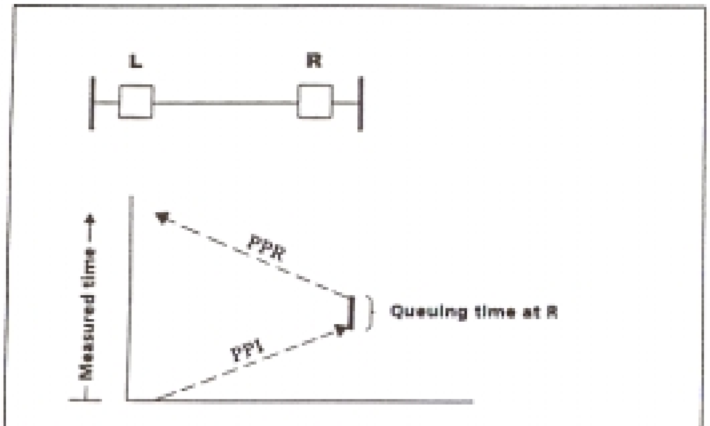

Figure 6. Ping-pong measurement

The phase angle of small load current is influenced by line-charging current, particularly on long EHV lines. Therefore, DML is only used whenever the load current is above 2 amperes rms (on a 5 ampere base). DML looks for a perfectly centered "nest" of the adjusted received time tag within the local negative half-cycle of phase current. If the channel delay is under compensated (Figure 7) or overcompensated (Figure 8), the nesting is off-center and the receiving terminal measures this deviation and calculates a corrected channel delay compensation value. DML is used on two-terminal lines only.

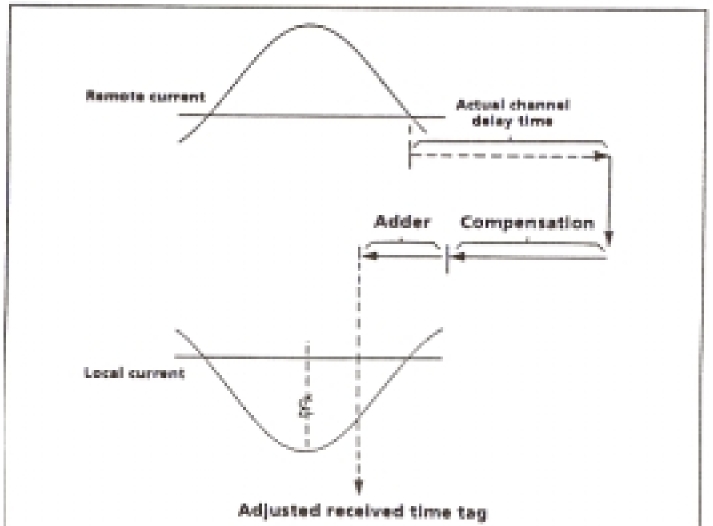

Figure 7. DML Measurement, channel delay undercompensated

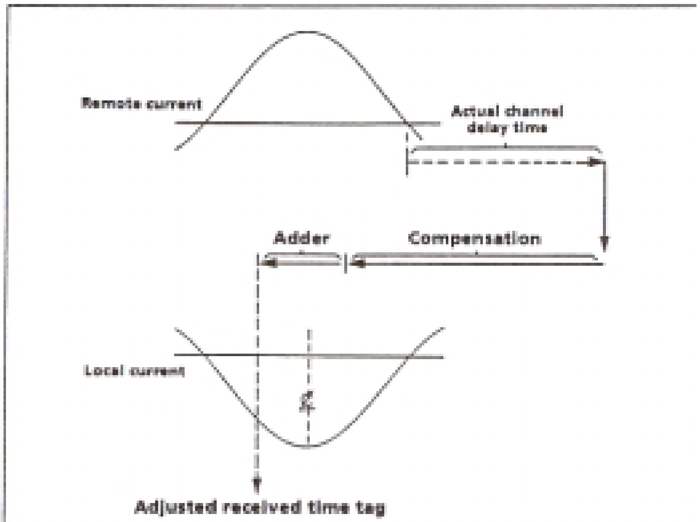

Figure 8. DML Measurement, channel delay overcompensated

Summary of Channel Delay Measurement

Whenever the channel is working in both directions, Ping-Pong delay measurement is performed and may be used to automatically calculate the channel delay compensation. This is true for two-terminal and three-terminal lines. On two-terminal lines only, whenever load current above two amperes is flowing, DML is used as a more accurate method of delay measurement - not subject to error if the outgoing and return delays are different.

MODEM FIELD TESTING

It has been explained that a 7200 bps modem is used to provide digital communications for charge comparison whenever the medium is an analog voice-grade circuit (300 - 3000 Hz), over leased-line or microwave. The performance of a modem of this bit rate, working in a substation environment, must be proven by field testing. In particular, the performance of the modem during nearby power system faults, had to be demonstrated. (In contrast, the field performance of the other charge comparison communications circuits - wide-band direct digital and fiber-optics - has already been field-proven on other teleprotection systems.)

In order to conduct these field tests, modem field test units ("MFTUs") were designed and built. The MFTU generates a steady test pattern, along with special codes for Ping-Pong Initiate and Ping-Pong Response. Bit errors are detected and counted over ten minute intervals. Bit error rates of 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5} are cumulated. All significant bit errors are recorded. If the channel is completely quiet, only "Day Reports" (every midnight) are recorded, including round-trip delay (Ping-Pong). Any loss-of-channel conditions are recorded. Any changes in Ping-Pong are recorded. Input terminals are provided to accept a contact closure from the operations alarm on an external Digital Fault Recorder (DFR). This way a correlation between modem performance and power system faults or other disturbances can be made, using the time-of-day clocks in the MFTU and the DFR.

Modem field testing started in August, 1990. Tampa Electric Company, Southern California Edison Company and Public Service Electric and Gas Company have participated in these tests. An open wire installation proved to be unworkable during nearby power system faults. A long (200 mile) multi-hop analog microwave application was error-free during nearby power system faults, but did occasionally experience fading, or other loss-of-channel conditions, which were not coincident with faults or other power system disturbances. A leased-line application has experienced high bit error rates during shunt capacitor switching operations, but no errors during nearby faults. At the time of the writing of this paper, this leased-line application is undergoing further investigation.

One observation regarding the modem field testing: the great majority of microwave loss-of-channel conditions, and all the leased line high bit error rates during shunt capacitor switching, occurred in only one direction or the other. In other words, both circuits (outgoing and return) did not fail at the same time. This tends to support the concept, previously mentioned, of treating the outgoing and return circuits as effective "dual" parallel channels: in case of failure of the channel in one direction only, trip at one terminal on charge comparison and sequentially trip the other terminal on loss-of-load.

CONCLUSION

This paper has presented the basic concepts of a digital approach to the communications requirements of a new transmission line protection scheme. The three major communications-related problem areas of conventional current differential relaying have been addressed and, in large measure, resolved. In many transmission line applications, the resulting protection scheme, called charge comparison, offers a viable alternative to the more traditional distance-based pilot relaying schemes.

ACKNOWLEDGMENTS

The authors would like to thank Public Service Electric and Gas Company, Southern California Edison Company and Tampa Electric Company for their cooperation in conducting modem field tests.

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Robert J. Ince after four years in the U.S. Air Force, graduated RETS Electronic School 1972. Attended Brookdale Community College 1978, Broward Community College 1981. Joined Westinghouse Relay Instrument Division 1973 as a Relay System Test Technician. Transferred in 1981 to Westinghouse Relay Instrument Division, Coral Springs as Relay System Test Supervisor.

Joined Dowty Control Technologies (formerly Dowty RFL Industries) in 1985 as a Customer Service Field Engineer and is presently in Technical Sales for Dowty's protective relay communication products.

Discussion

J. G. Andrichak, G. E. Alexander, M. G. Adamiak, and R. C. Patterson (GE Meter and Control, Malvern PA): The authors are again to be congratulated on a clever use of digital communications in the integration of a new current differential technique. The discussers ask the authors to comment on the following aspects of their paper:

The authors make the statement that "charge comparison is not intended for use over a metallic pilot wire" citing reasons such availability of copper pairs, induction from fault currents, and GPR. Yet in the next paragraph, the authors recommend using "Analog voice circuits over leased telephone lines" which are typically copper, often run parallel to power lines, and are subject to GPR. Could the authors comment on this apparent inconsistency.

The authors make reference again to the paper "Mica 500kV Protection" (ref. 3) and cite the use of positive half cycle transmission for phase information and negative half cycle for ground information. In the cited reference, dual phase comparison was implemented via a combination primary and backup communication system. One of the requirements of the system, however, was high speed single phase tripping. Could the authors comment on how high speed single phase selection is accomplished in their relay as well as what the speed penalties may be.

Manuscript received February 19, 1992.

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The authors would like to thank Mr. Rockefeller, Mr. Cheetham and Messrs. Andrichak, Alexander, Adamiak and Patterson for their interesting comments and questions.

Mr. Rockefeller asked about the "UHS" (Ultra High Speed) logic. If the instantaneous current exceeds 12 A (positive for phase, negative for residual) peak for 2 ms, then a high-priority message is sent to the other terminal. The receiving terminal asserts a trip signal unless it experiences at least one sample of 10 A or more, of opposite polarity, over the same real time as the 12 A was sampled. A moving "time window" is selected at the receiver terminal, to assure proper operation for both tripping and blocking in the presence of improper channel delay compensation (up to ±4 ms). If there is 12 A infeed to the fault at both ends, the operation is the same at both terminals. If the high current is at one end only, then the strong terminal is tripped by a "CCT-U" (Charge Comparison Trip-Ultimate) message which is sent from the weak terminal.

The UHS creates a breaker trip signal in as little as 11 ms, including 4 ms for auxiliary trip relay operation, when using a 56 K channel. The authors believe that this trip time is close enough to 1/2 cycle to allow the use of the term "UHS". When used over a 7.2 K channel, the fastest trip times are about 1-1/2 cycles. This certainly does not qualify as "UHS", but we didn't want to use different terms for 7.2 K and 56 K systems.

The UHS message is sent before the normal "CCD" (Charge Comparison Data) message, which must wait for the end of the half-cycle. The CCD message is also sent, as a back-up to the UHS signal. Either message can cause tripping.

The 12 A peak level was selected because the rms equivalent (approximately 9 A) is well above peak load.

DC offset usually helps UHS tripping, but sometimes can cause a short delay due to a "minor loop" (short half-cycle) that does not exceed the 12 A peak level.

The UHS for three-terminal lines (future software) will require approximately coincident receipt of UHS messages from the two remote terminals. The receiving terminal will then look for a large negative current over the same real time. If this blocking action does not occur, then tripping occurs just as in the two-terminal line application.

Mr. Rockefeller asked about A/D "overflow". The communication channel limits at 15-3/4 A peak. There are six message bits assigned to magnitude, so resolution is 1/4 A peak. The local current resolution is 1/8 A.

Mr. Cheetham has suggested that the 56 K design has been compromised by adapting this design from the 7.2 K version. The authors agree that this is a reasonable assumption. In fact, Page 4 of the paper states that "- - - the original fear was that the design for the higher bit rates would be compromised". However, the paper goes on to say "This fear is unfounded". It turned out that the short word message structure and the tolerance for large errors in channel delay compensation, both of which are required for 7.2 K, are also very advantageous when working at 56 K.

The authors agree with Mr. Cheetham's observation that "- - - the more independent features - - - the more difficult the coordination - - -". However, the number of extra features that we added to the basic charge comparison routine is actually quite small. The major added functions are:

* UHS
* Weak Feed Trip
* Zero Current Messages (Similar to open breaker keying in a permissive scheme)
* Double-Excursion Inhibit

When compared to other pilot relaying schemes, the degree of complexity is actually very minimal.

The use of a half-cycle Fast Fourier Filter was considered. Instead, we elected to use charge measurement, based on high-rate sampling (2 kHz) of instantaneous current. Reasons:

* Mimic filter not required.
* We sample asynchronously to the power system current.
* Simple computer algorithm (addition instead of square roots).

Three-terminal lines (future software) will perform the equivalent of a phasor addition of the two received remote currents. This is done by a relatively simple look-up table that takes angle difference into account (based on the adjusted received time-tags of each received current message). In effect, this achieves the "full Vector information" transfer as suggested by Mr. Cheetham.

Messrs. Andrichak et al point out that charge comparison is "not intended for use over metallic pilot wire", but is suitable for "leased telephone lines". The authors agree that this may be viewed as an apparent inconsistency. Our answer is that when used over a leased telephone line, "SPO-A" (Service Performance Objective - A) lines, only, are recommended. In order to qualify as SPO-A, the line must be free of interference "before, during and after" power system faults. In order to meet this requirement, the telephone line will probably not serve as a "metallic antenna" from one substation to the other, as pilot wires do. To meet an SPO-A requirement, the leased telephone lines that are used for charge comparison will probably be routed through one or more central offices and will contain some nonmetallic segments which will serve to break up the ground potential rise and the longitudinal inductive interference problems associated with metallic pilot wires.

The authors agree that the conference paper by Mr. Lefrancois (Ref. 3 of the paper) describes a dual protection arrangement where the primary and back-up are opposite polarities. Charge comparison uses only one scheme, so single-line-to-ground faults will develop a trip signal on every half-cycle, with phase tripping and residual tripping alternating. This introduces a maximum half-cycle speed penalty for single-pole tripping schemes, but no penalty for three-pole tripping schemes.

Manuscript received April 20, 1992.