# COMBINED-SEQUENCE PHASE COMPARISON RELAYING

Presented
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## INTRODUCTION

The simplicity and elegance of current-only protection systems combined with explosion in data communication provide a powerful option to the present generation of relay engineers. [1]

At the same time thousands of transmission lines in USA and abroad offer data transport medium in the form of Power Line Carrier. [5]

This paper explores the application of current-only, phase comparison protection system as particularly well-suited for Power Line Carrier communications.

The phase comparison principle for line protection was introduced in the 1930's and was widely used a decade later, worldwide.

An example of one of the early designs is shown in figure 1, please note the presence of vacuum-tube as the phase comparison element.

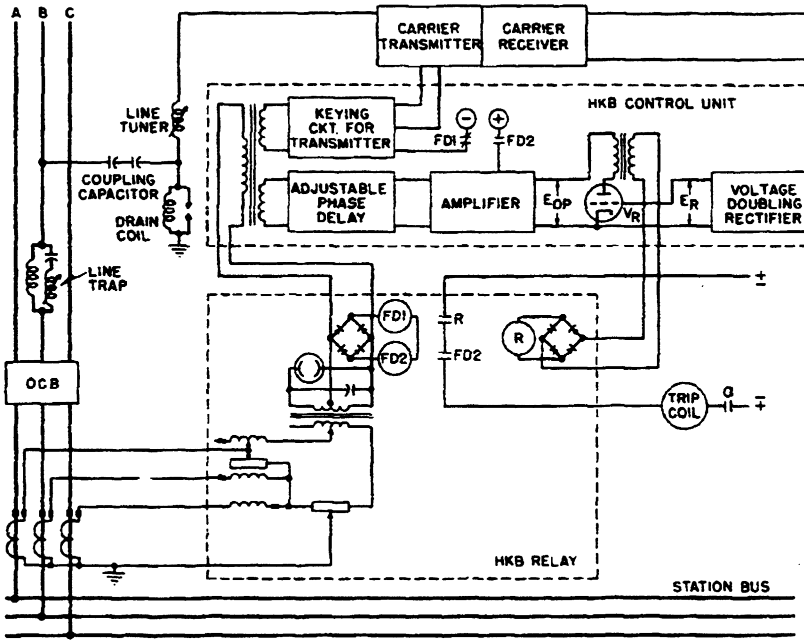


Figure 1. Basic Schematic Connections of the Type HKB Relaying System

Subsequently, following progress of electronics - transistor, integrated circuit and finally microprocessor found their applications in phase comparison relaying.

# PRINCIPLE OF OPERATION

Current only systems, compare the currents measured at the terminals of the transmission line. In a phase comparison system the phase relationship determines the state of the protected line.

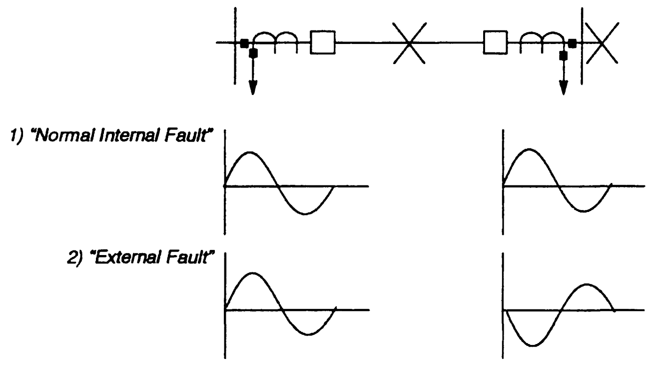


Figure 2. Phase Comparison, Fault Recognition

For an internal fault, the currents are essentially "in phase" at the terminals of the transmission line. For an external fault; the currents are 180° out of phase. Figure 2 illustrates the concept.

In order to minimize the modulation requirements of the PLC equipment, the three-phase currents are synthesized into a single quantity. This quantity is proportional to the positive, negative and zero components of the input currents in the general form:

$I_T = I_1 C_1 + I_2 C_2 + I_0 C_0$

where

$I_1$, $I_2$, $I_0$ are positive, negative and zero sequence components.

$C_1$, $C_2$, $C_0$ are weighting coefficients.

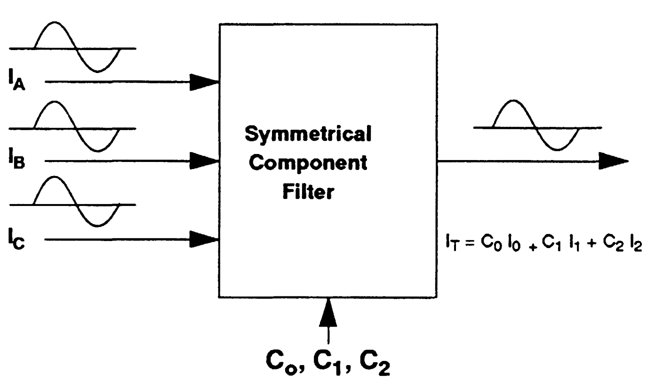


Figure 3. Symmetrical Component Filter

The $I_T$ (combined sequence waveform) is of sinusoidal nature at the frequency of power system (60 or 50 Hz wherever you may live).

Thus the Power Line Carrier is modulated at the comfortable 120 to 250 baud.

The sinusoidal waveform $I_T$ is converted into square-waves for phase comparison as illustrated in figure 5 and 6.

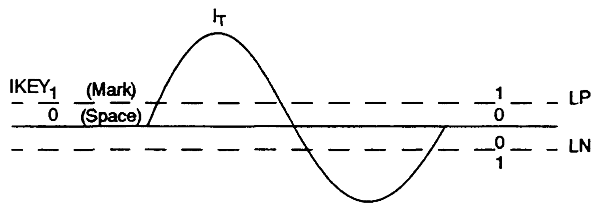
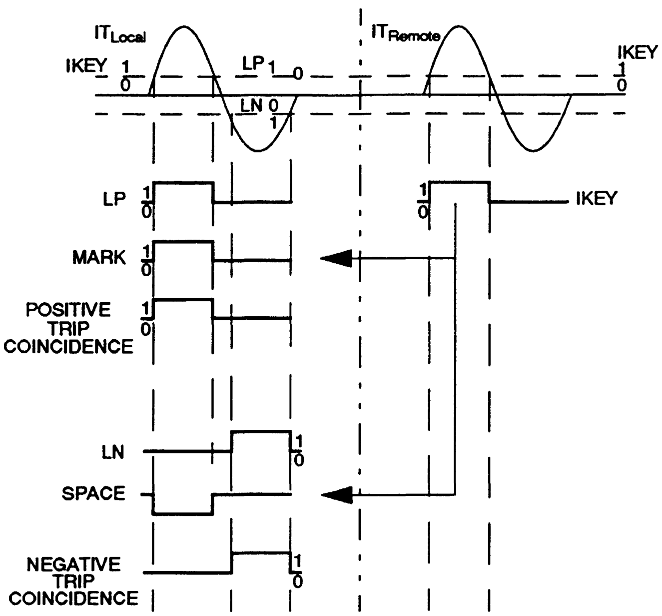


Figure 4.

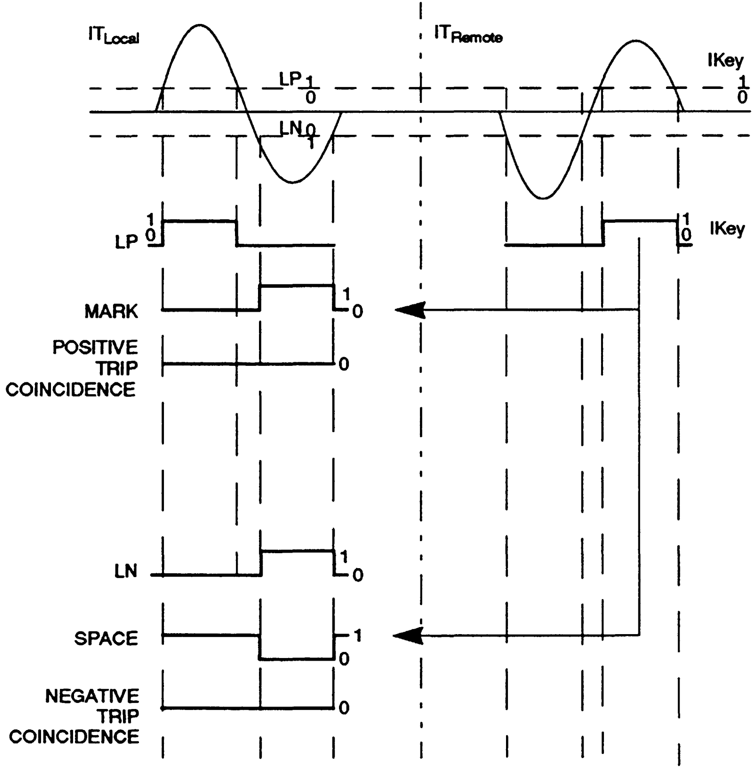
## Local Positive (LP) and Local Negative (LN) and IKEY

The LP and LN waveforms are used to represent a phase of positive and negative half-cycle of the $I_T$ signal at a local terminal.



NOTE: For ON-OFF Power Line Carrier only negative half-cycle comparison is performed.

Figure 5. Internal Fault



NOTE: For ON-OFF Power Line Carrier only negative half-cycle comparison is performed.

Figure 6. External Fault

.The local positive LP is defined as a logic “1” in the positive region of $I_T$ above the setting LP; otherwise it is a “0”.

The local negative LN is defined as a logic “1” in the negative region of $I_T$ below the setting LN: otherwise it is a “0”.

The IKEY level is provided to define the threshold generating the square wave to be sent to the remote terminal. The IKEY level is defined in the positive region. Above the threshold level, the local terminal will “key” a logic “1” to the remote terminal.

## FSK Power Line Carrier and Audio Tone Applications

**Internal Fault** – The signals generated during an internal fault are shown in figure 5. Note that the local and remote currents are essentially in phase. The local terminal generates the LP and LN signals.

The IKEY signal is generated in the remote terminal and transmitted over the communications channel (for example, power line carrier) and received in the local terminal as MARK and SPACE signals subjected to communication propagation delay (CPD).

The local terminal provides compensation for CPD by delaying local quantities LP and LN as shown in figure 7 (LDT).

The MARK signal and the LP signal are ANDed and a “positive trip coincidence” state is asserted. The same is true with the SPACE and LN signals. The two are ANDed together to produce a “negative trip coincidence” condition. The composite COUT signal is generated as shown in figure 7. The pilot trip PLT is asserted if 4 msec timer is satisfied.

## External Fault and Load Condition

For an external fault (and load condition), the signal relationship is shown in figure 6. Due to the current directions at both ends, the currents into the relaying units in the local and remote sites will be 180° out of phase. When ANDing the MARK and LP and the SPACE and LN signals, the "positive trip coincidence" and "negative trip coincidence" conditions will be zero all the time. Therefore, the COUT output will be constant logic "0".

## On-Off Power Line Carrier Applications

As seen in figures 5, 6, and 7 the negative half-cycle comparisons only are performed. ON-OFF PLC operates in the "quiescent" mode, i.e., during normal load state of the transmission line the carrier is turned "off", this corresponds to the SPACE asserted to continuous "1" state at the receiver.

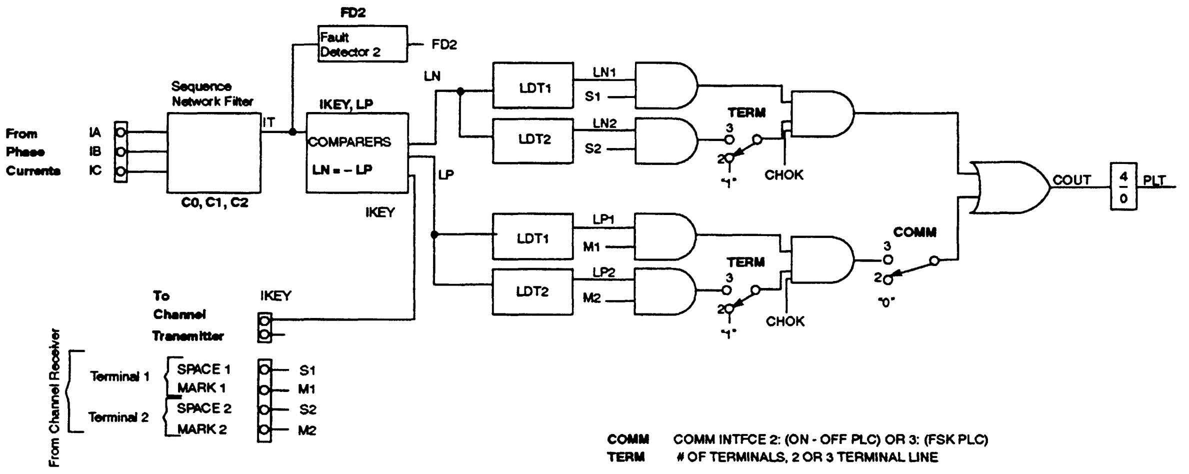


Figure 7. Phase Comparison Logic

**Internal Fault** – For internal fault the SPACE and LN signals produce positive coincidence COUT as shown on figure 5. The pilot trip PLT is enabled if 4 msec timer is satisfied (figure 7).

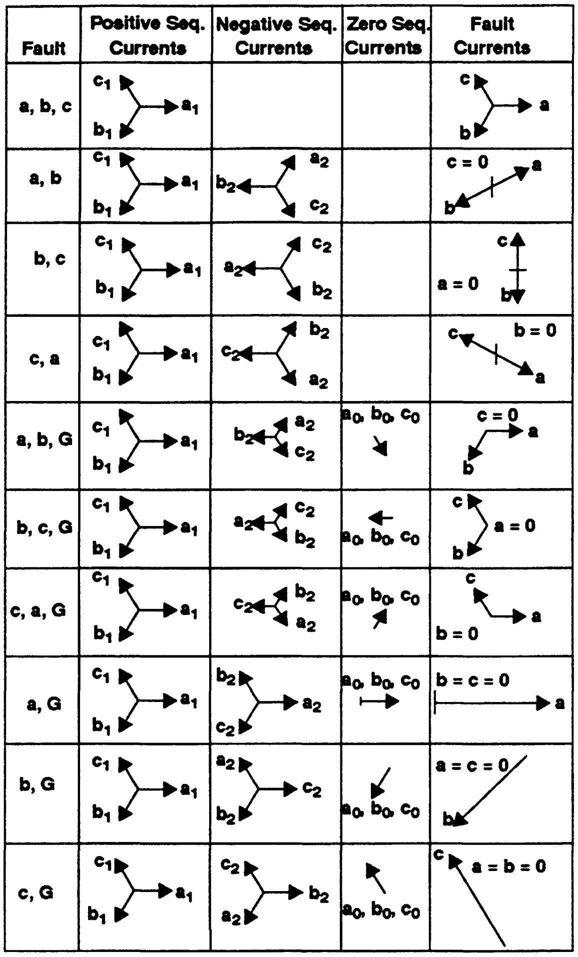
**External Fault** – The external fault is illustrated in figure 6; remember that only negative half-cycle comparisons are performed. The LN and SPACE comparison results in deasserted COUT ("0" state) and a pilot trip is blocked. The ON-OFF PLC applications are therefore referred to as "blocking" systems.

## Three-Terminal Applications

If the system is used for a three-terminal application, there will be two sets of MARK and SPACE signals received from the remote locations. As illustrated in figure 7, the M1 and S1 (from remote terminal 1) and M2 and S2 (from remote terminal 2) are compared to the respective LP1, LN1, LP2 and LN2 signals delayed by the respective LDT1 or LDT2. It is extremely important that the settings reflect the true channel delays of the communications channel. The correct phase comparison is totally dependent on the proper channel delay measurement.

## COMBINED - SEQUENCE METHODS

For reference figure 8 illustrates positive, negative and zero sequence components for various types of faults.



Assumes $Z_1 = Z_2 = Z_0$

Figure 8. Sequence Currents for Various Faults.

### Magnetic Sequence Filters

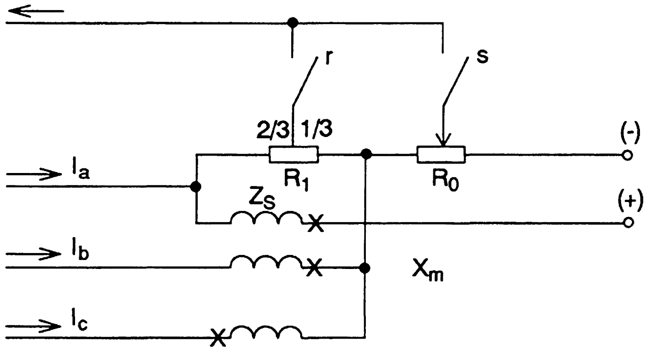
One of the early designs incorporated 3 winding saturating transformers as illustrated in figure 9 [2]. The combined output quantity variations are shown in Table 1 below.

The problem list included:

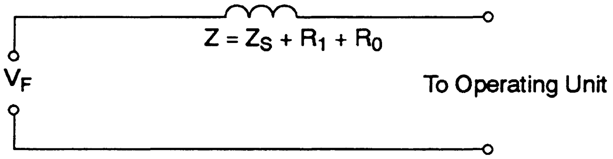
- Rather crude choice of output combinations of sequence quantities.
- Very poor transient response.

Table 1: Typical Sequence Network Combinations

| Network Type | Switch r | Switch s | $X_m$ = | Notes | $V_F$ reduces from: Equation to Equal |
|---|---|---|---|---|---|
| Positive Sequence | closed | open | $R_1/\sqrt{3}$ | interchange $I_b$ and $I_c$ | $2R_1I_1$ |
| Negative Sequence | closed | open | $R_1/\sqrt{3}$ | as shown | $2R_1I_2$ |
| HCB Composite | open | closed | $R_1/\sqrt{3}$ | Interchange $I_b$ and $I_c$ | $2R_1I_1 + (R_1 + 3R_0)I_0$ |
| HCB-1 and SKB Composites | open | closed | $1.46R_1$ or .191 ohms | as shown | $-0.2I_1 + .462I_2 + (R_1 + 3R_0)I_0$ |



(a) Sequence Network



(b) Equivalent Circuit

Figure 9. Composite Sequence Current Network.

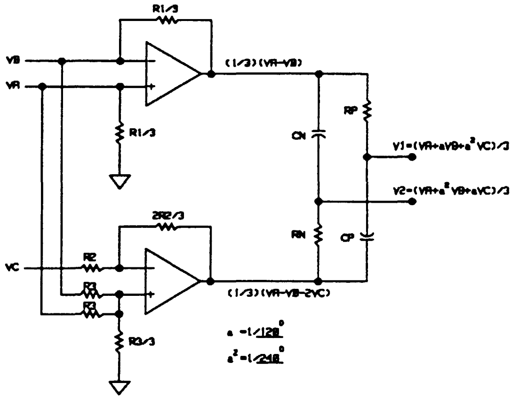


Figure 10. Electronic Sequence Network

## Electronic Sequence Filter

This brilliant and simple circuit [4] dates back to late 1970's and still is in wide use today. While solving most of the problems with the magnetic filter described above, this design shares standard headaches of analog circuits:

- Temperature drift,
- Component ageing,
- Power supply level sensitivity.

The adjustment flexibility is also somewhat limited.

## Numerical Sequence Filter

This design (microprocessor software implementation) being fully numerical eliminates all the above mentioned impairments, offering at the same time total, almost seamless adjustment flexibility.

The algorithm is based on Clarke's components [3] presented in 1938 and suggested earlier by Lewis in 1917 (sic!).

The following relationships exist:

$$I_\alpha = \frac{1}{3}(2I_a - I_b + I_c)$$

$$I_\beta = \frac{1}{\sqrt{3}}(I_b - I_c)$$

Where $I_a$, $I_b$, $I_c$ are 3 phase currents

$$I_1 = \frac{1}{2}(I_\alpha + jI_\beta)$$

$$I_2 = \frac{1}{2}(I_\alpha - jI_\beta)$$

$$I_0 = \frac{1}{3}(I_\alpha + I_b + I_c)$$

where $I_1$, $I_2$, $I_0$ are positive, negative and zero sequence current components.

And finally, the numerically derived combined-sequence output.

$$I_T = I_1 C_1 + I_2 C_2 + I_0 C_0$$

where $C_1$, $C_2$ and $C_0$ are system settings.

Typical Relative values of these settings are:

$C_1 = 0.1$
$C_2 = 0.2$
$C_0 = 0.7$

Thus providing greatest contribution (ergo - sensitivity) to $I_T$ from zero sequence (phase-ground faults) and lowest contribution from positive sequence (load and 3Ø faults).

Commercially available mathematical programs enable relay designer (and user if so desired) to quickly simulate fault conditions and review the resulting waveforms.

The following figures illustrate the balanced load of 5A followed by a mild (10A) A-G fault and the resulting positive sequence $I_1$, negative sequence $I_2$, combined sequence $I_T$ and finally square waves used for phase comparison.

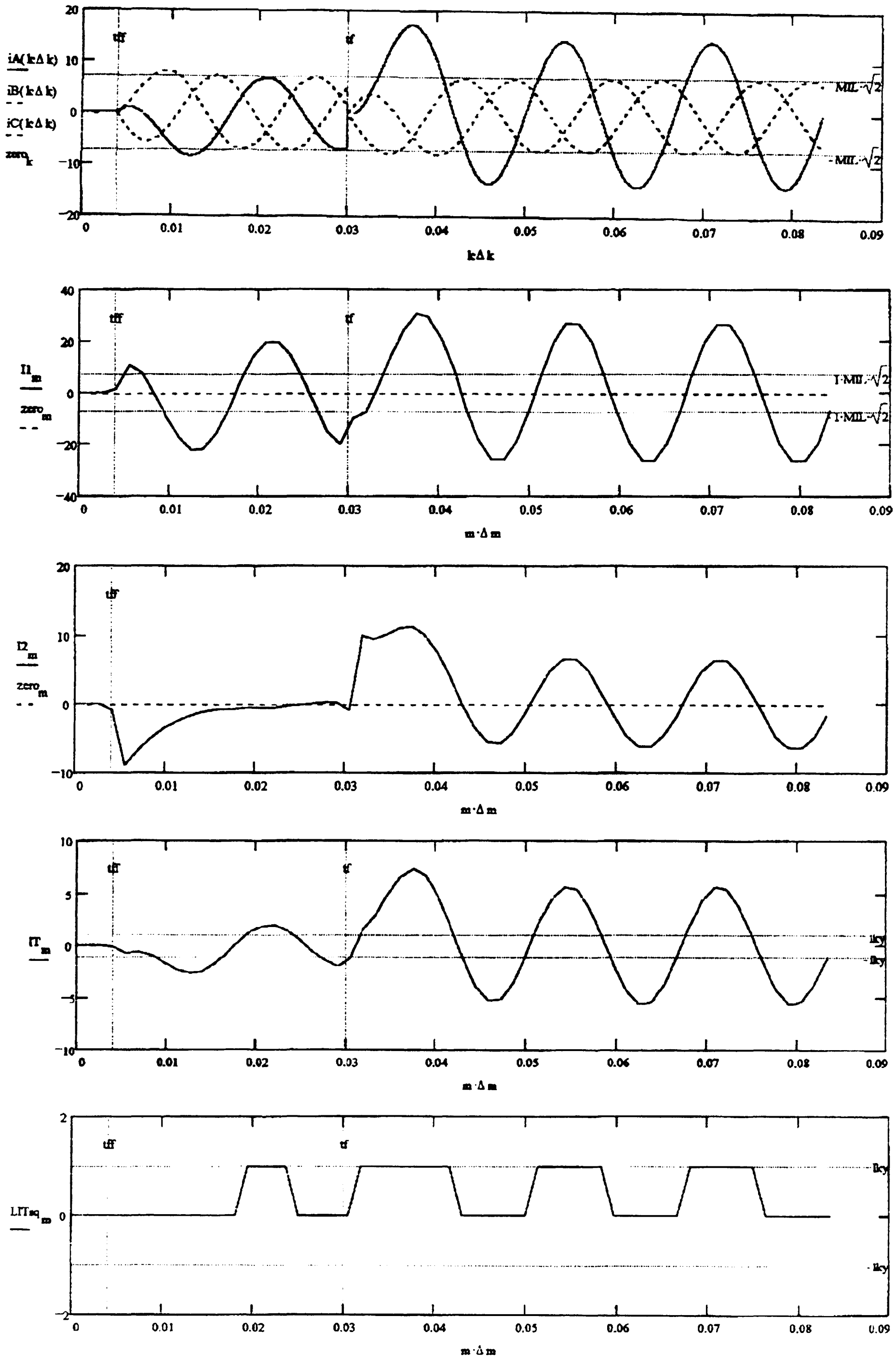


Figure 11.

## COMMUNICATION EQUIPMENT INTERFACE

Communication equipment such as Power Line Carrier, Audio-Tones, Analog Microwave, etc. is an integral part of phase comparison protection system.

The interface between protection and communication equipment shall have the following properties:

- High noise immunity to combat harsh HV substation environment.
- Faithful, bias-distortion free reproduction of "square-wave" signals, IKEY, MARK and SPACE.
- FAIL-SAFE operation.
- Flexibility to interface to various types of communication equipment.

Optically isolated outputs and inputs allowing usage of external station battery with "on" current in the order of 10 to 20 mA are the best choice answering the above criteria.

Typical interface is shown in the block diagram form:

The functions of the top four signals are obvious as discussed above.

The failure output from protection equipment is asserted due to power failure or internal self-check failure (microprocessor based). The purpose of this signal is disabling the communication equipment from producing false results at the other end of the protected line.

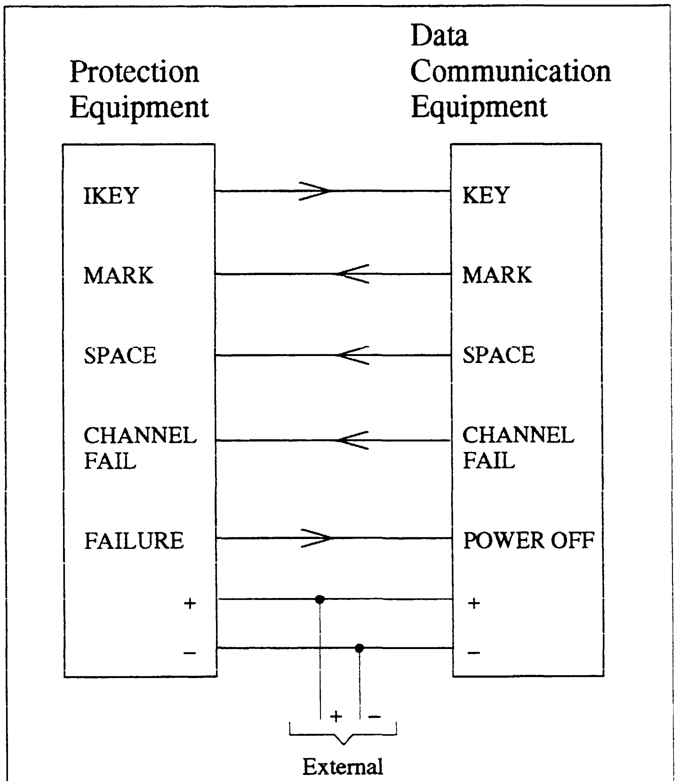


Figure 12

# CONCLUSION

Combined-sequence phase comparison protection systems offer inherent advantages over impedance-based relaying:

- Immunity to power system swings
- Immunity to extremes of source impedance ratio
- Excellent response to high impedance faults
- High speed fault clearing (subcycle operation)
- Applicability to protection of very short as well as very long lines
- Independence from loss of potential

This type of protection is particularly advantageous in applications where Power Line Carrier is the only choice of communication medium.

Very low communication modulation rates, in the order of 120 to 250 baud allow reliable operation over low grade communication channels.

Numerical implementation of the combined-sequence filter eliminates the problems with earlier magnetic and electronic designs.

The microprocessor design provides the user with high degree of flexibility to configure the protection system to the line characteristics.

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[2] "Applied Protective Relaying", Westinghouse Electric Corp.

[3] "Circuit Analysis of AC Power Systems", Edith Clarke, John Wiley and Sons 1943

[4] "A Current Differential Relay System", S.C. Sun, R. Ray, IEEE 1982

[5] "Power Line Carrier Channel", M. Sanders, R. Ray, Georgia Tech, May 1996

# BIOGRAPHICAL SKETCH

**Janusz W. Dzieduszko** is a native of Poland, and a MSEE graduate of the Academy of Mining and Metallurgy in Cracow. He has experience in Engineering Management, Design Engineering and Marketing in the fields of Power T&D Industry: SCADA/EMS, Protective Relaying, Load Management, and Data Communications. He is a member of IEEE Power Engineering Society. He speaks fluent Polish, and Russian.

He joined Westinghouse Electric Corporation in 1967 as a Senior Design Engineer. In 1979 he became Manager of Hardware Development for Brown Boveri Control Systems, Inc. (BBC). There he was responsible for design of Remote Terminal Unit, Communication Front End for DEC computers. In 1984, as manager of Power Line Communications for General Electric Company, he was responsible for Load Management system. In 1985 He joined Westinghouse Electric Corporation as Senior Design engineer responsible for Hardware and Data Communications Subsystems of Integrated Substation Protection and Control System (WESPAC). He continued to hold that position, following a 1989 merger with ABB, until 1991. He was then promoted to Manager Product Development. He directed development of many protective relays. He has directed and completed work of major parts of International ABB development project COMSYS involving ABB locations in Sweden, Switzerland and Finland.

He holds two patents in Digital Data Communication and has two additional Pending Patents in Data Acquisition. He is the author of "WESPAC System Self-Diagnostic Features", "On The Upcoming Second Revolution In Protection Systems", and co-author of "Communication Interface Specification" published by EPRI.