SELECTION OF TRANSMISSION LINE RELAYING SYSTEMS

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INTRODUCTION

This paper describes a rational, practical approach one might use to select one transmission line relaying system from the many that are traditionally used. It attempts to simplify some of the subtle choices the user must make by leading to a selection based on power system constraints, and on preferred practices for the particular user.

Seldom is a clear choice evident that would represent the only relaying system useable in a given case. Often several of the schemes will be applicable, and in these cases, an effort is made in the logic to cause the selection of the least costly system.

Though certain basics remain constant, new factors are constantly added that open the application of a given relaying system to a wider area. Some past examples of this are:

PROBLEM	SOLUTION
1. Transfer tripping over a carrier channel was considered unreliable because the fault could block carrier transmission.	1. Developed the Unblocking scheme that allows tripping for 150 ms following loss of channel provided the distance relays operate.
2. Phase Comparsion was fault-incidence-angle sensitive and tripping could be delayed an extra half cycle.	2. Developed the Dual Phase Comparison system to permit tripping on **both** half cycles.
3. Voice could not be conveniently added to a frequency shift carrier system.	3. Developed voice adapter for amplitude modulation of the carrier.
4. Very-high-resistance ground fault could not be recognized by ground distance relay.	4. Added logic in Uniflex to allow time window for tripping on **directional** unit in the absence of blocking carrier.
5. Series capacitors distort the relationship between current and voltage for a given fault location.	5. Developed current-only system with correct response, irrespective of frequency and capacitor gap response.
6. No fault current at one terminal to operate fault detector.	6. Use change detector to respond to decrease or shift as well as increase of current.

SYSTEM DESCRIPTION

The basic forms of pilot protection involve the transmission of relaying information from one terminal of a protected-line section to the other by means of a suitable channel – power-line carrier, microwave, tones, or a pair of wires. The systems can be categorized as directional-comparison, phase-comparison, or pilot-wire depending on the type of sensing relays used. The schemes can be further subclassified as blocking, unblocking, or transfer trip depending upon the use made of the transmitted signal.

TABLE I - DIRECTIONAL COMPARISON RELAYING SYSTEMS

	BLOCKING CARRIER SYSTEMS (ON-OFF CARRIER)					UNBLOCKING CARRIER SYSTEMS (FREQUENCY SHIFT CARRIER)					TRANSFER-TRIP SYSTEMS (WIDE-BAND AUDIO TONE)						
	Phase and Ground Distance			Phase Distance Directional Ground Overcurrent		Phase and Ground Distance			Phase Distance Directional Ground Overcurrent		Permissive Overreaching					Underreaching	
											Phase and Ground Distance			Phase Distance Directional Ground Overcurrent		Direct	Permissive
RELAY FUNCTION	Pilot Only	Pilot & Zone 2 Timer	Pilot Zone 1 (phase & ground) & Zone 2 Timer	Pilot Only	Pilot & Zone 1 (phase & ground)	Pilot Only	Pilot & Zone 2 Timer	Pilot Zone 1 (phase & ground) & Zone 2 Timer	Pilot Only	Pilot & Zone 1 (phase & ground)	Pilot Only	Pilot & Zone 2 Timer	Pilot Zone 1 (phase & ground) & Zone 2 Timer	Pilot Only	Pilot & Zone 1 (phase & ground)	Pilot Only	Pilot Only
Zone 1 Phase Distance			LDZ		LDZ			LDZ		LDZ			LDZ		LDZ	LDZ	LDZ
Forward Set Phase Distance, Carrier Trip and Carrier Stop	LKD			LKD	LKD	LKD			LKD	LKD	LKD			LKD	LKD		
Zone 2 Phase Distance Time, Carrier Trip and Carrier Stop		LKD	LKD				LKD					LKD	LKD				LKD
Reverse Set Phase Distance Carrier Start	LD-1	LD-1	LD-1	LD-1	LD-1												
Directional/Instantaneous Ground Overcurrent, Carrier Trip and Carrier Stop, Dual Polarized				LRG	LRG				LRG	LRG				LRG	LRG		
Zone 1 Ground Distance			LDGZ		LDGZ			LDGZ		LDGZ			LDGZ		LDGZ	LDGZ	LDGZ
Forward Set Ground Distance, Carrier Trip and Carrier Stop	LDG					LDG					LDG						
Zone 2 Ground Distance Time, Carrier Trip and Carrier Stop		LDG	LDG				LDG	LDG				LDG	LDG				LDG
Instantaneous Overcurrent	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI
Carrier or Tone Auxiliary Relay	DBL	DBL	DBL	DBL	DBL	DUL	DUL	DUL	DUL	DUL	DUL	DUL	DUL	DUL	DUL	TTL	TTL
Output Package, AR Trips, Reclose and Breaker Failure Initiation, Reclose Blocking, Indicating Lights	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO	UIO
Channel	TC-10	TC-10	TC-10	TC-10	TC-10	TCF-10	TCF-10	TCF-10	TCF-10	TCF-10	DIT-3	DIT-3	DIT-3	DIT-3	DIT-3	DIT-1	DIT-3

Directional-Comparison – Directional relay elements at both line terminals sense the direction of the fault, either toward or away from the protected line section. A **blocking** scheme uses the transmitted signal (carrier or tone), initiated when a fault is sensed **away** from the protected line, to block tripping at the other terminal. When the fault is on the protected line, a blocking signal is not transmitted from either terminal. The absence of blocking signals allows directional elements at both terminals to operate in response to the fault and initiate circuit breaker tripping.

An **unblocking** scheme utilizes a frequency shift channel to provide a continuous blocking (guard) signal. Directional elements shift the transmitter to the trip frequency only if they sense a fault **toward** the protected section. For a short period of time following loss of guard (whether caused by a shift to trip or by the fault shorting the carrier signal), tripping is permitted at the receiving station. Thus, simultaneous loss of guard and directional relay operation initiates circuit breaker tripping. For faults outside the protected line section, guard is received at one terminal and the directional relay does not operate at the other, so tripping is prevented.

In contrast to these schemes which use the transmitted signal to prevent tripping, **transfer-trip** pilot protection **requires** the reception of the transmitted trip signal to permit tripping. Thus, when an internal fault occurs, directional relay operation in conjunction with the shift from the guard to the tripping signal from the other terminal sets up tripping.

In the preceding descriptions, only directional relays were mentioned as the tripping elements. However, pilot systems always use distance relays for phase protection and often for ground protection. Distance relays are directional but, further, have a distinct area of coverage irrespective of fault current variations.

TABLE II – TRANSMISSION LINE SOLID STATE PHASE COMPARISON RELAY SYSTEMS

RELAY FUNCTION	POWERLINE CARRIER CHANNELS				WIDE BAND FREQUENCY SHIFT AUDIO TONE CHANNELS		
	Short and Medium Lines		Long Lines		Short and Medium Lines	Long Lines	
	Phase Comparison		Distance Phase Comparison		Phase Comparison	Distance Phase Comparison	Current Comparison
	Blocking On-Off	Unblocking Dual-Comparer Frequency Shift	Blocking On-Off	Unblocking Dual-Comparer Frequency Shift	Transfer Trip Dual-Comparer	Transfer Trip Dual-Comparer Phase Distance	Segregated Phase Comparison
Phase Comparison Relay, FD-1 Carrier Start and FD-2 Arm Fault Detectors	SKBU-1						
Phase Comparison Relay, Dual Comparer Single Fault Detector		SKBU-2A			SKBU-2A		
Phase Comparison Relay, FD-1 Carrier Start and FD-2 Arm Fault Detectors			SKBU-1				
Phase Comparison Relay, Single Fault Detector, Dual Comparer				SKBU-2A		SKBU-2A	
Phase Comparison Relay, Current Change Detector, Instantaneous Overcurrent Units							SPCU-1A (2 or 3)
Phase Distance Offset MHO Relay			SKDU-3	SKDU-3		SKDU-3	
Instantaneous Overcurrent Units, High Set for Direct Trip, Phase and Ground	Optional	Optional	SIU	SIU		SIU	
Output Package, AR Trips, Target Lamps and Breaker Failure and Reclose Initiation	SRU	SRU	SRU	SRU	SRU	SRU	SRU

A transfer-trip scheme can be classified as either **overreaching** or **underreaching,** depending on the setting of the relays that key the channel. In the overreaching arrangement, the distance relays are set to reach beyond the next bus in the protected direction. These are called zone 2 distance relays. In the underreaching scheme, the distance relays are set short of the next bus, but the distance relays at the two stations are set to overlap one another to assure that at least one operates for all faults on the protected line. These are called zone 1 distance relays. The scheme is "direct" if tripping is initiated for an internal fault by the distance relay at one terminal and by the received signal at the other. Actually in this scheme, most faults are cleared by the distance relays operating at both terminals without the need of signal reception.

The other underreaching scheme is "permissive," and, in this arrangement, reception of the trip frequency alone cannot produce tripping. Another local relay (usually an overreaching distance relay or a directional overcurrent relay) supervises tripping on signal reception.

Phase-Comparison – Sensing elements at each terminal derive a single-phase voltage from the phase and/or neutral currents at each terminal. That voltage is used to key the signal transmitting device on alternate half cycles and to operate one or more fault detectors that prepare the circuitry for tripping.

For a fault **external** to the protected line, the current-derived voltages at the two terminals are essentially 180 degrees out of phase. Thus, during the interval when either terminal attempts to trip, a signal is received from the other terminal to provide the necessary restraint.

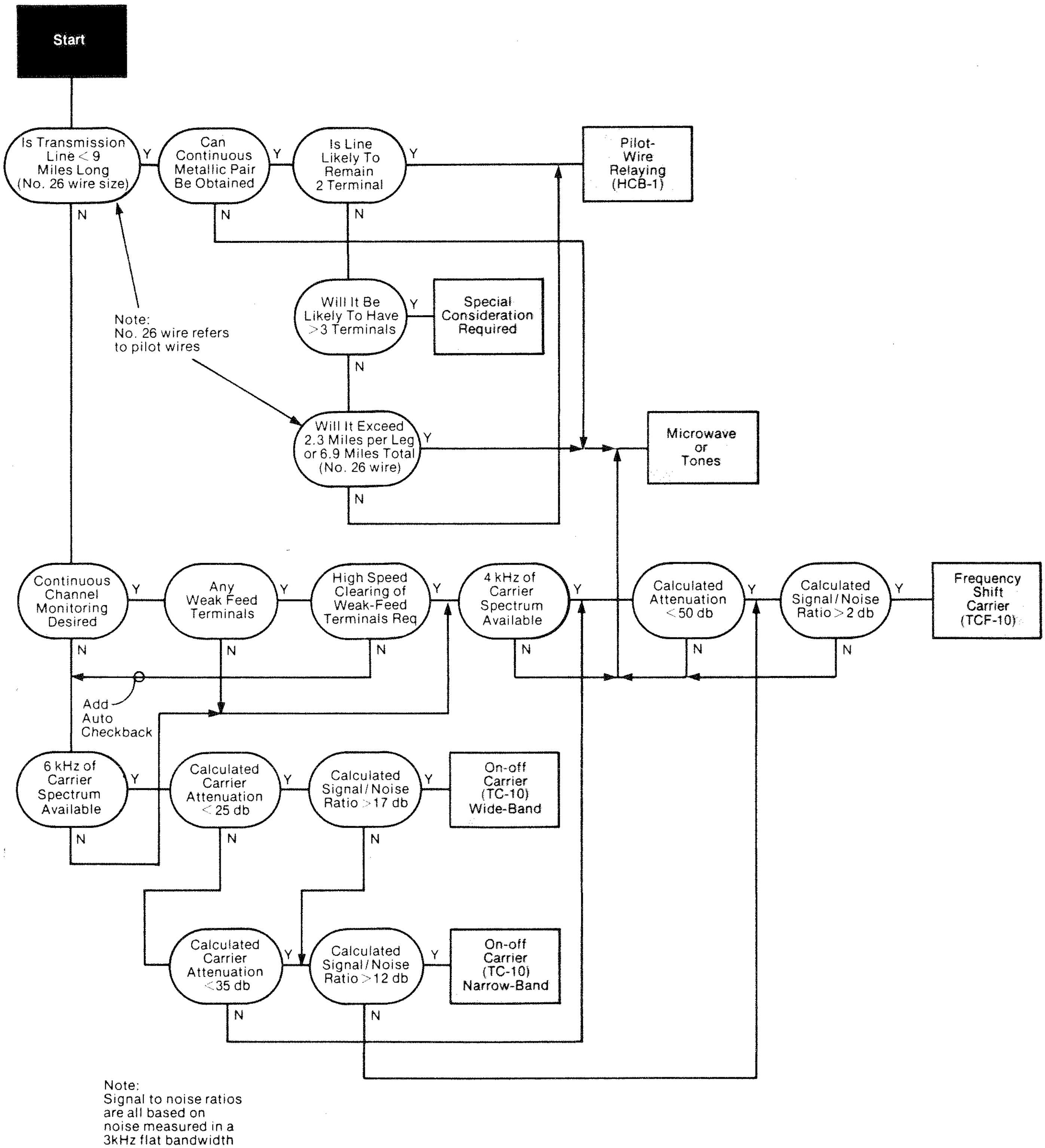

Figure 1. Typical logic for transmission line pilot relaying channel selection.

When the fault is **internal,** the current-derived voltages in the "on-off" schemes are such that each transmits its blocking signal on the same alternate half cycle and removes the blocking signal on the intervals between. During the half-cycle periods that the blocking signal is absent, tripping is permitted at both terminals.

In the "frequency-shift" schemes, **mark** and **space** frequencies are transmitted on the alternate half cycles. Keying of the transmitter to mark or space is controlled by the local current-derived voltage. The receiver converts the received frequency into a digital signal, which is compared with the current-derived voltage at that location. Comparison of the phase position of the local current-derived voltage and the mark or space signal received from the other terminal allows the fault to be identified as internal or external. Since **both** half cycles of the **local** quantity are compard to the mark and space signals derived from the **remote** quantity, tripping is possible on either half cycle.

As with directional-comparison systems, it is possible to operate a phase-comparison scheme in the blocking, unblocking, or transfer-trip mode.

Segregated phase comparison relaying uses an independent system for each phase for comparing the relative current directions at each terminal of the transmission line. It establishes whether a fault is external or internal and, if internal, on which phase (s) it is located. A variation of this scheme uses a delta & ground configuration, to make two comparisions over two channels, one for the difference of two phase currents and one for residual current. Three types of communications channels are used with this system: tones, frequency shift carrier, or a carrier data-set. A separate tone transmitter-receiver combination is used for each current being compared. The data-set transmitter encodes a signal that incorporates information relative to three (or less) currents and this signal, in turn, is decoded at the receiver for comparison by the relaying system.

Pilot-Wire – Current-derived voltages at each terminal are compared directly over a pair of wires in this scheme. For an external fault, the relative polarities produce restraint from tripping. Supervisory relays are frequently applied to assure the integrity of the pilot wire circuit. Also, remote tripping can be accomplished as an adjunct to pilot-wire relaying. Pilot-wire relaying is economical, but it is only applicable to short line sections because of pilot wire limits.

CHANNEL SELECTION

One of the prominent influences in the selection of a pilot relaying system is the type of channel to be used. That, in turn, is regulated by utility practice, available spectrum, line characteristics (transpositions, insulation class, noise level), availability of a channel dictated by other requirements and, to some extent, personal choice.

Where a wire line can be obtained that is suitable for transmission of 60 hertz low voltage signals and confidence exists in its integrity, and where the protected line is suitably short (to conform to the pilot pair limits), pilot wire relaying should be considered for application. It is a first class high speed, sensitive, discriminating, economical relaying system.

Figure 1 defines some of the limits that influence the selection of a communications channel. Certain key facts are involved in the chart:

1. Pilot wire limit is 2000 ohms (total loop) for two terminal HCB (or HCB-1) applications, 500 ohms per leg for three terminals, 1.5 microfarads shunt capacitance for two terminal and 1.8 microfarads (total) for three terminal.
2. HCB (or HCB-1) relaying is applicable to transmission lines having no more than three terminals.
3. Spectrum availability is critical for power-line-carrier and dependent upon receiver bandwidth.

4. Channel attenuation is critical for power-line-carrier and related to receiver sensitivity and signal-to-noise ratio.
5. Signal-to-noise ratio restrictions are then related to type of receiver.

If pilot wire relaying is not applicable, tones on metallic pairs or microwave should be considered for short lines and carrier or microwave for longer lines. The availability of microwave between all terminals for which the pilot relaying system is being applied will greatly influence the use of that channel for relaying. Seldom can microwave be justified for relaying use alone. Single side-band carrier with its large information capability may also be available for relaying use.

Carrier can be used only if a band can be found in the frequency spectrum in which interfering signals will not disrupt the normal relaying signal transmission. The magnitude of the interfering signal is as important as frequency separation. The 6 kHz and 4 kHz criteria specified in Fig. 1 are based on the relaying receiver being set at a maximum sensitivity and the interfering signals being sufficiently below the allowable level to avoid undesired response. However, the 6 kHz and 4 kHz figures are intended only as an approximate guide. For example, where 40 dBm (10 watt) signals are coupled directly to the same coax and each full-level transmitter signal becomes to the adjacent receiver a very strong interfering signal, as much as a 10 kHz separation may be required between the two frequencies.

A reasonable limit of 25 dB total channel attenuation (including hybrids and LC units) is suggested for on-off wide band (TC-10) carrier. This limit is based on a 15 dBm clear weather signal at the coax, a 1·5 dB signal deterioration allowance, and a 17 dB signal/noise ratio (noise measured in a 3 kHz flat bandwidth).

The 35 dB limit for the narrow band on-off (TC-10) carrier is based on a 10 dB higher channel rating inherent in the receiver sensitivity and made possible by the better noise rejection quality of the front-end filter.

The frequency shift channel (TCF wide band for pilot applications) limit of 50 dB considers a − 25 dBm receiver sensitivity setting, a 15 dB margin and a 40 dBm transmitted signal. The 2 dB signal-to-noise ratio for the frequency shift carrier is much lower than that for the on-off carrier because of the difference in the received-signal sensing techniques.

The weak-feed-terminal question relates to terminals having inadequate generation behind them (or inadequate ground sources) to produce reliable operation of a distance or directional overcurrent relay at that terminal for a fault on the protected circuit. This requires special weak-feed relayng based on undervoltage (and/or ground overvoltage) sensing, and also having other elements that are included for security. It is most compatible with Unblocking schemes which are not susceptible to false tripping due to loss-of-voltage, because of the continuous blocking carrier.

Where **high speed** clearing is not required for the "weak" terminal, the Blocking scheme is the best choice. With no normal carrier transmission, no shift or shut-off is required when an internal fault occurs. Clearing of the strong terminals requires **no action** at the weak terminals. Emergency voice carrier cannot be applied at the weak terminal. It is assumed that sequential tripping is possible at the weak-terminal following strong-terminal tripping and redistribution of fault current, or that tripping is not required at that terminal.

RELAYING SYSTEMS FOR MICROWAVE OR TONE CHANNELS

When the logic for selection of the pilot relaying channel indicates that microwave or tone channels should be used, the choice can be made by the process shown in Fig. 2.

A series capacitor in the station is the first consideration because a capacitor introduces distinct

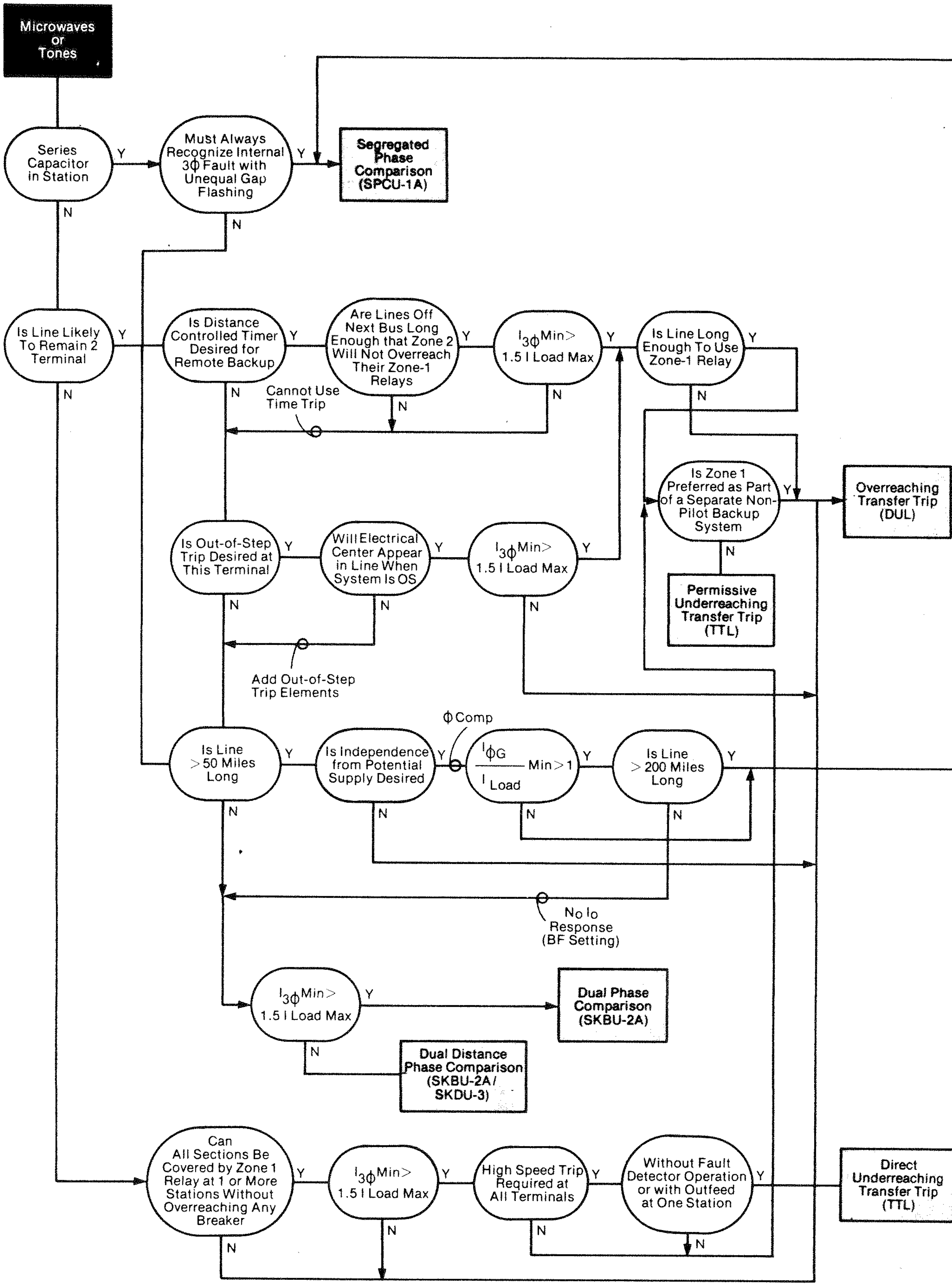

Figure 2. Typical logic for selecting a microwave or tone relaying system.

problems in the protective relaying for transmission lines terminating in that station. Distance relays sense incorrectly the direction to a fault at the capacitor line junction. This problem is experienced by the relay on the lines with series capacitors and by those on adjacent lines with or without series capacitors. Phase-comparison systems are not afflicted with this difficulty.

An **internal** three-phase fault with unequal gap flashing will produce "through" negative-sequence and zero-sequence current flow so that a system using a filter with a heavy zero-sequence weighting factor will incorrectly sense this as an external fault. Where this type of fault is considered to be significant and other devices will not detect it, the **segregated** phase-comparison (SPCU-1A) system must be used. In the segregated system, each individual phase is relayed as an independent circuit and comparison between each of these quantities at the two line terminals by the relaying system is accomplished over the communication channel.

When conventional phase-comparison systems can be applied, one significant consideration is load current. The fault detector for three-phase faults should reset on the maximum load flow. Although fault detector operation would not produce tripping, it would represent an infringement on security because the system would be continuously armed. The dual distance phase-comparison (SKBU-2A/SKDU-3) system alleviates this load criticallity by incorporating a distance relay as a fault detector. It is insensitive to the high power factor conditions normally associated with load flow. The qualifying term "dual" means that a frequency-shift channel is used and tripping is possible on **either** half cycle. In the single comparer systems using on-off carrier, tripping can occur only during the "off" half cycle.

For two-terminal applications with no series capacitor problems, personal preference exercises a strong influence in the selection. The customary judgement process used in choosing between overreaching and underreaching transfer-trip systems is formalized in Fig. 2. The logic allows selection of the less expensive phase-comparison system only if system parameters permit.

The 50 mile limitation is a conservative limit beyond which consideration will be necessary of the effect of line capacitance on current level at the two ends of the line for a low magnitude remote ground fault. For longer lines, having adequate ground fault current level for internal faults ($I_{\phi G}/I_{Load}$ greater than 1), settings can be used that cause the relay to ignore zero sequence current. This makes it less susceptible to capacitance effects, but also makes it less sensitive to internal ground faults (because of the dependence on negative sequence current with its lower weighting factor than that for zero sequence current). The 200 mile limit is based on the inability to get sufficient negative sequence current over the line for a ground fault at the end of a transmission line that long.

An underreaching transfer trip system (Uniflex TTL module) is not allowed by the logic in Fig. 2 unless a fault detector overcurrent relay can be used. This avoids possible false trips due to potential circuit failure. The **direct** underreaching system is selected only for three-terminal applications where all faults can be recognized by zone 1 relays at one or more stations, where all terminals require high-speed tripping, and where fault detecting relays (including phase undervoltage and zero-sequence overvoltage) at all terminals cannot recognize all internal faults.

FREQUENCY-SHIFT CARRIER

When the frequency-shift carrier (TCF) channel is indicated, the relaying scheme is selected as outlined in Fig. 3.

Again, a series capacitor in the station sharply divides the areas of application for phase-comparison and directional-comparison unblocking systems. Also, for the short and moderately long two-terminal lines for which the back-up and out-of-step trip functions are to be independent of the primary relaying system, a dual phase-comparison unblocking system (SKBU-2A) is selected. Ground fault current limitations may restrict the choice of composite filter phase comparison (SKBU-2A) to only short lines.

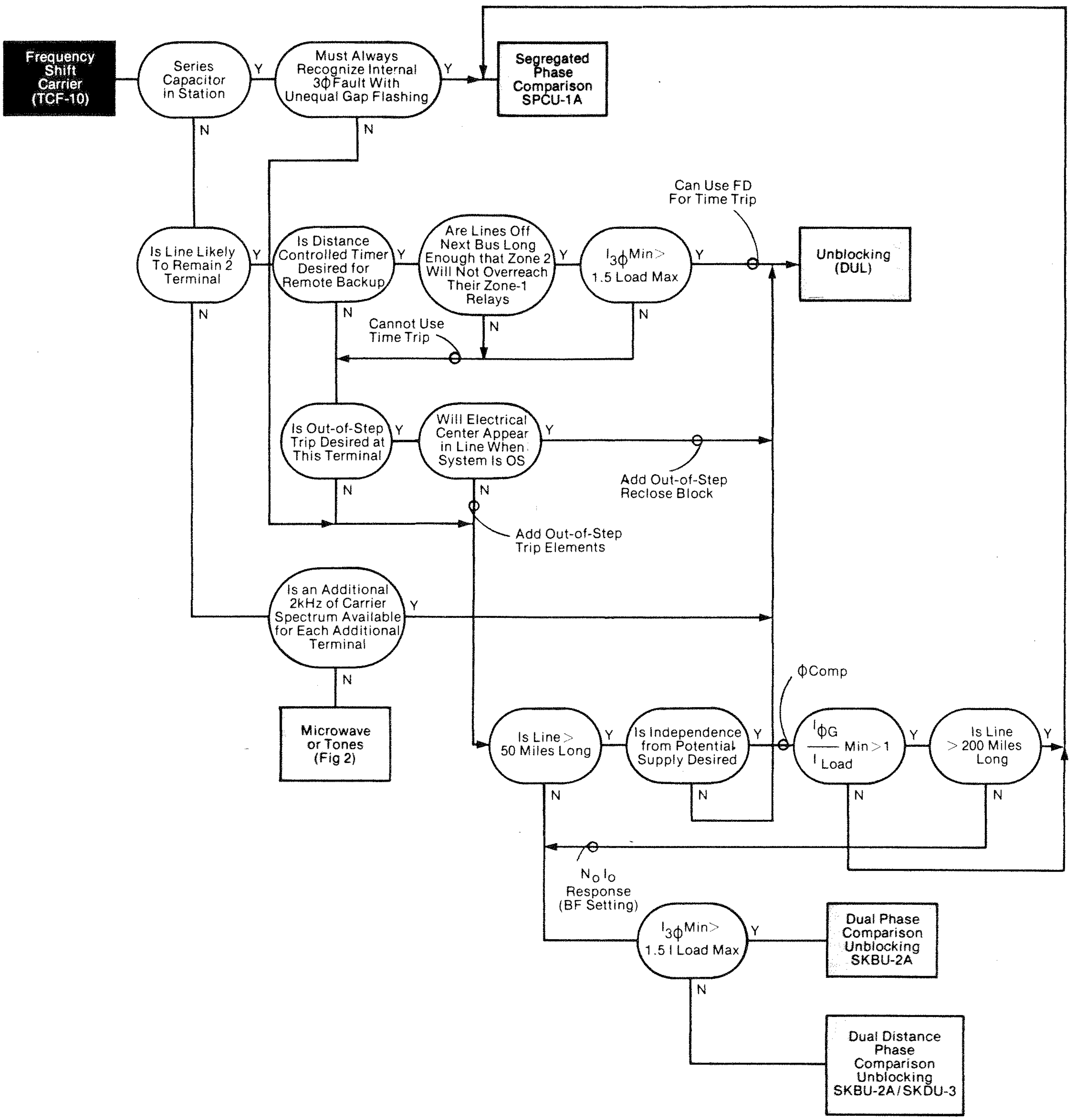

Figure 3. Typical logic for frequency shift carrier relaying system selection.

For three-terminal frequency-shift carrier applications, the unblocking system is preferred if sufficient carrier frequency spectrum is available. Three-terminal phase-comparison systems are possible but difficult, and they are not allowed by this selection process in the interest of restricting the choices to the flexible, easily realizable cases.

ON-OFF CARRIER

The selection process for a directional-comparison or phase-comparison on-off carrier system is shown in Fig. 4. The presence of a series capacitor in the station, as in the other cases, forces the use of a phase-comparison system. The lack of desire to incorporate a distance-controlled back-up timing function in the primary relaying, or to use the primary phase-distance relays to clear out-of-step conditions, also encourages the choice of the less expensive phase-comparison system for all but extremely long-line two-terminal applications where ground fault current level will permit.

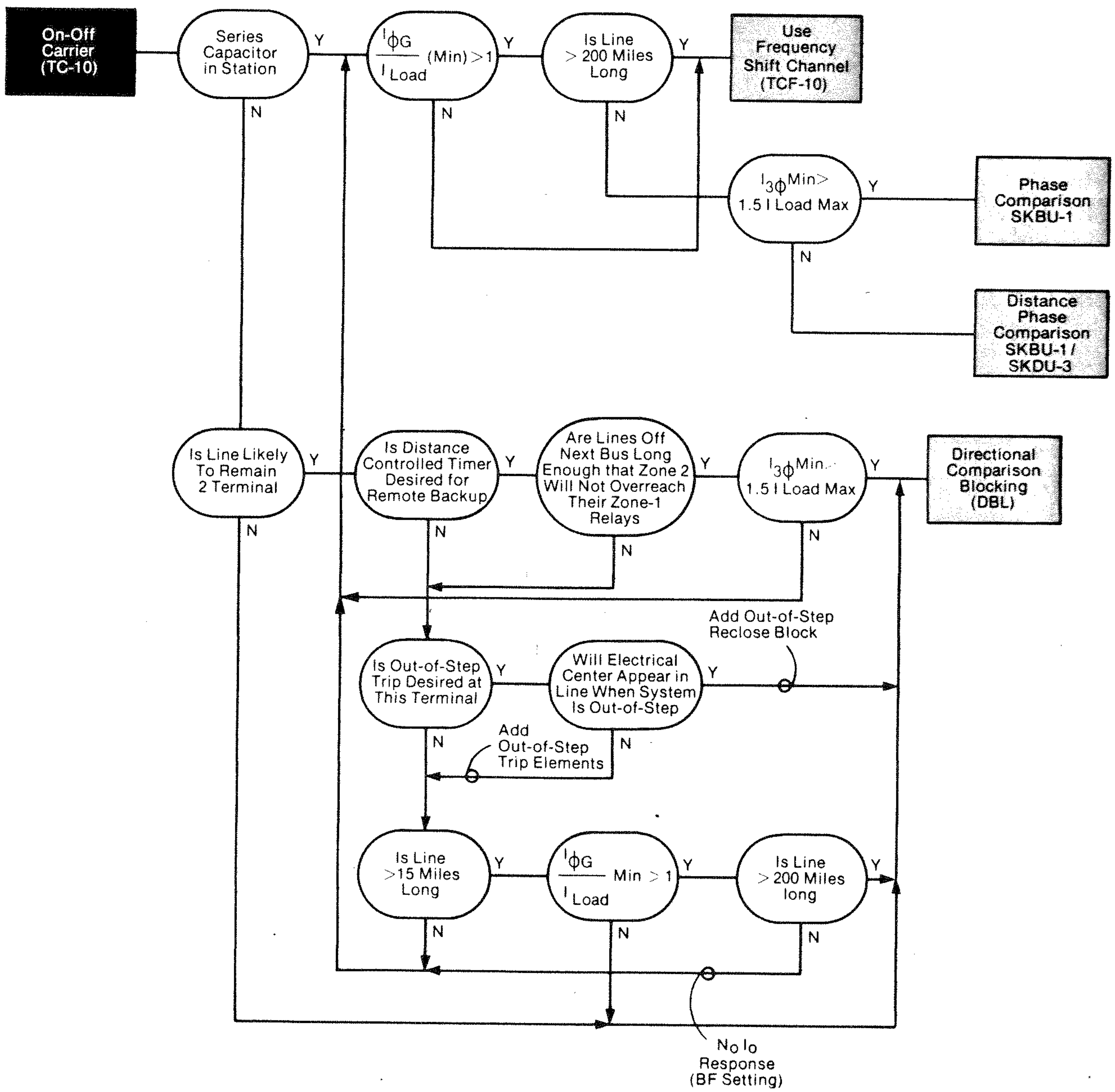

Figure 4. Typical logic for selecting an on-off carrier relaying system.

For three-terminal lines, the directional-comparison system has the distinction of requiring no relaying action at weak-feed locations for the high-speed clearing to take place at the strong-feed locations for internal faults. This characteristic is based on the premise that there is no continuous use made of the carrier system at the weak-feed location. Otherwise, stopping of the weak-feed carrier becomes mandatory for the internal fault to clear.

As with frequency-shift systems, three-terminal applications of phase-comparison systems are not selected because of their inflexibility and restrictive nature. This does not mean that system characteristics never permit successful applications of three-terminal phase-comparison schemes. In fact, many such installations have performed excellently for many years.

ADDITIONAL SYSTEM OPTIONS

Any of the pilot protection systems selected can be equipped with a number of additional options to give the systems the desired degree of redundancy or to provide some additional feature required by a particular application.

High-Set Overcurrent Trips – This alternate is available in all of the standard systems and is highly recommended in applications where faults can be located on the basis of current magnitude alone. Air-gap units (overcurrent elements with gapped iron circuit) are available with no more than 17 percent overreach for maximum asymmetry due to dc component of fault current. They should be set 25 percent greater than the maximum current for an external fault in the forward or reverse direction. When high-set overcurrent trips can be used, they provide an excellent form of backup that is fast, simple, inexpensive, and independent of all other sensing elements and the communications channel.

Zone 1 Phase and Ground Relaying – Phase and ground-distance relays are not as restricted in application as the high-set overcurrent relays, but the protected line must have sufficient length so a fault at the balance point will produce adequate operating energy for the relays to operate reliably. They are not responsive to external faults, they are fast, and they require no information from the remote terminal via the communication channel. They provide an excellent support function to most pilot relaying systems and are available as a part of all standard systems.

T2 Timer – Any system equipped with overreaching phase and ground-distance relays may drive a timer to provide remote back-up. In recent years there has been an increasing use of local back-up systems to cover the breaker-failure contingency. However, there is still a place for distance-controlled timers. A single timer is adequate for the phase and ground functions with separate indication.

Out-of-Step Relaying – One approach for selecting an out-of-step relaying system is shown in Fig. 5. Although many other considerations enter into the selection, this logic does show some of the predominant influences in establishing the proper choice, once the desired philosophy is determined.

The philosophical input is not particularly easy to develop. It is dependent on whether instability can develop on the system under consideration, where the electrical center appears to be when instability does develop, whether the out-of-step condition produces current high enough to cause an interruption problem with the very high recovery voltage that may accompany out-of-step tripping, what the minimum internal three-phase fault current will be, and what the maximum load current can be. All of this must be developed within reasonable contingency limits, and each factor may manifest its critical case with a completely different system arrangement from that for all of the other factors. The logic shown in Fig. 5 aids in the selection of the particular out-of-step system to be used, through examination of the results expected from the system and from a consideration of the operating practices of the user. The single-blinder scheme uses distance elements having a characteristic on a resistance-reactance plot consisting of two parallel lines centered about the origin and sloping at 15 degrees from the vertical. The dual-blinder scheme uses two such units, the second having a wider spacing than the first. The tomato scheme uses one distance unit having a circular characteristic on a resistance-reactance plot and another having as the name implies, a shape on the R-X diagram similar to a tomato and surrounding the other characteristic. Usually the three-phase unit of the Zone-2 relay in the transmission line relaying scheme is used for the inner circle with a separate (shorter) timer producing the outer characteristic. All out-of-step relaying variations indicated may be accommodated in the standard systems.

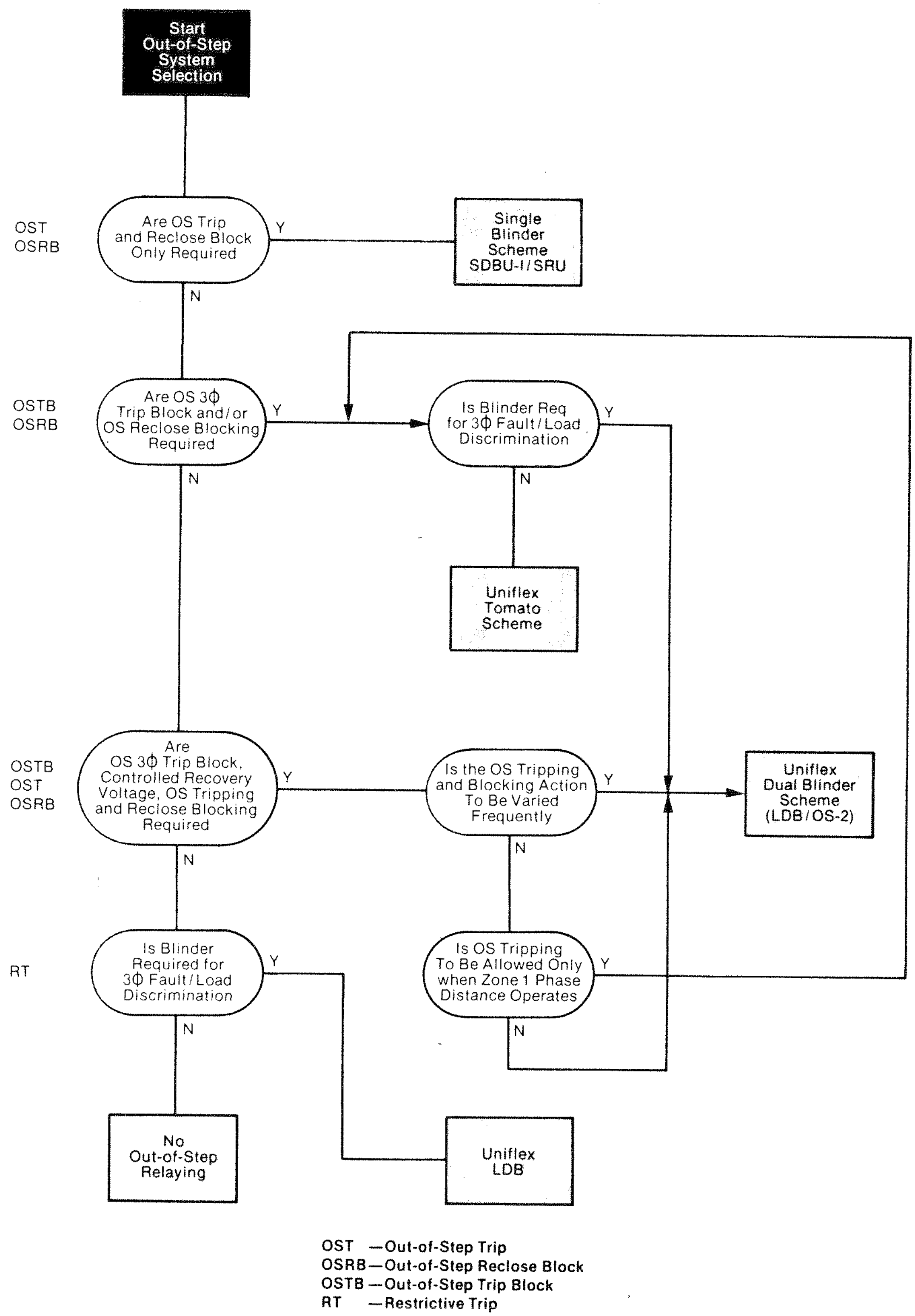

Figure 5. Typical logic for selecting an out-of-step relaying system.

CHOICE OF RECLOSING SYSTEM

Automatic reclosing is desirable in any application where it is expected that a fault may clear before the circuit is reenergized. For example, multi-shot reclosing relays are distinctly called for with overhead distribution applications because of their ability to improve service continuity. In transmission applications, reclosing relays are often used to provide a single high-speed reclosure when tripping is produced by pilot relaying, and then to provide one or more time-delayed reclosures in response to synchronism check or hot-bus dead-line control. Initiation of high-speed reclosing occurs in response to all high-speed tripping, with a further constraint customarily imposed (by a control switch contact) to prevent high-speed reclosing unless pilot tripping is in service.

CONCLUSION

There are many variations in the solid-state relaying systems that can be applied to transmission line pilot protection. The ones discussed briefly in this paper are those that have been developed by Westinghouse relay engineers in the interest of simplifying the application of pilot protection systems, both for the user and for the manufacturer.

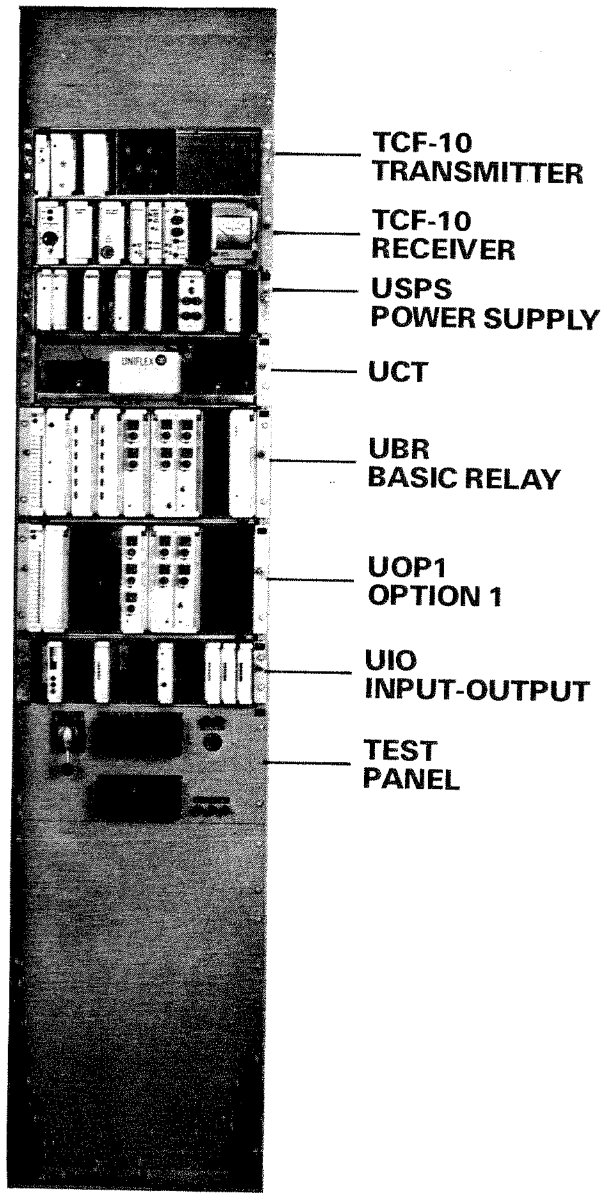

Figure 6. A typical directional comparison unblocking system is made up of various solid-state relays and components, selected to satisfy the requirements of the application.