7 Carrier-aided Protection of Transmission Lines

7.1 Need for Carrier-aided Protection

The main aim of the electrical power system is to maintain uninterrupted supply of electricity to consumers. Electrical faults, however, cause interruption to the supply. When a fault takes place it is detected by protective relays and the fault current is interrupted by the circuit breaker. The maintenance personnel must then rush to the fault location, rectify the fault, and restore the supply. This applies to permanent faults.

However, there is statistical evidence, as shown in Table 7.1, that about 80% of faults are not permanent but are transient. These faults are caused by breakdown of air surrounding the insulator. These faults can disappear by themselves, if the supply is briefly interrupted and the arc-path is allowed to de-ionize.

Table 7.1 Fault statistics

Type of fault	*Probability*
Transient	80%
Semi-permanent	10%
Permanent	10%

Thus, whenever a fault takes place, we can tentatively assume that a transient fault has interrupted the supply. We then wait for a short while before switching on the circuit breaker. This is known as *reclosure*. The reclosure can be carried out manually or automatically.

If the fault was indeed a transient one and the interruption was of a duration greater than the de-ionization time, then the reclosure would be successful, that is, there would be no recurrence of the fault. The typical de-ionization times for various system voltages are listed in Table 7.2.

Table 7.2 Typical de-ionization times

System voltage	*Typical de-ionization time*
66 kV	0.10 s
132 kV	0.17 s
220 kV	0.28 s
400 kV	0.50 s

If the fault is a permanent one, reclosure will be unsuccessful, i.e. the protective relay would immediately cause the circuit breaker to trip. Thus, in case of a transient fault, reclosure helps in keeping the downtime to a minimum and in increasing the availability of supply. Reclosure has different implications for low/medium voltage (LV/MV) and high or extra high voltage (HV/EHV) systems.

In low and medium voltage systems, a maximum of three consecutive reclosures are allowed. If the fault persists even after the third reclosure, i.e even when the third reclosure fails, then the circuit breaker is locked out and no more reclosures are allowed. The multiple reclosures in LV and MV systems help in burning out the object responsible for the fault, say, a tree branch, and thus in clearing out the fault.

Only one reclosure is allowed in HV/EHV systems because reclosure imposes arduous duty on the circuit breakers and other elements of the power system as the fault MVA is very large.

In HV/EHV systems, reclosure, if done sufficiently fast, helps in improving the stability of the system. This is so because as soon as there is an interruption in the system, the rotor angles of various generators start drifting apart and if they drift apart beyond a critical angle, the system loses stability. If, however, the supply is restored before this critical time elapses, the system can pull together and remain stable.

Since HV/EHV lines are generally tie lines, there is presence of source at both the ends. Thus, in order for the transient fault arc to be quickly quenched, the line must be instantaneously and simultaneously tripped from both ends, before a reclosure can be attempted.

The three-stepped distance protection for the entire line length does not meet the requirement of instantaneous and simultaneous tripping from both ends. Only about 60% of the length in the middle of the line gets high speed protection from both ends. For about 20% of line length, near each end of the line, i.e. a total of 40% of line length, the protection is instantaneous from the local end but is delayed from the remote end. This is shown in Figure 7.1. Thus, in order to be able to implement auto-reclosure, we need to augment the distance protection so that instantaneous tripping from both ends for 100% of the line length becomes possible.

Carrier-based schemes help us in achieving this objective.

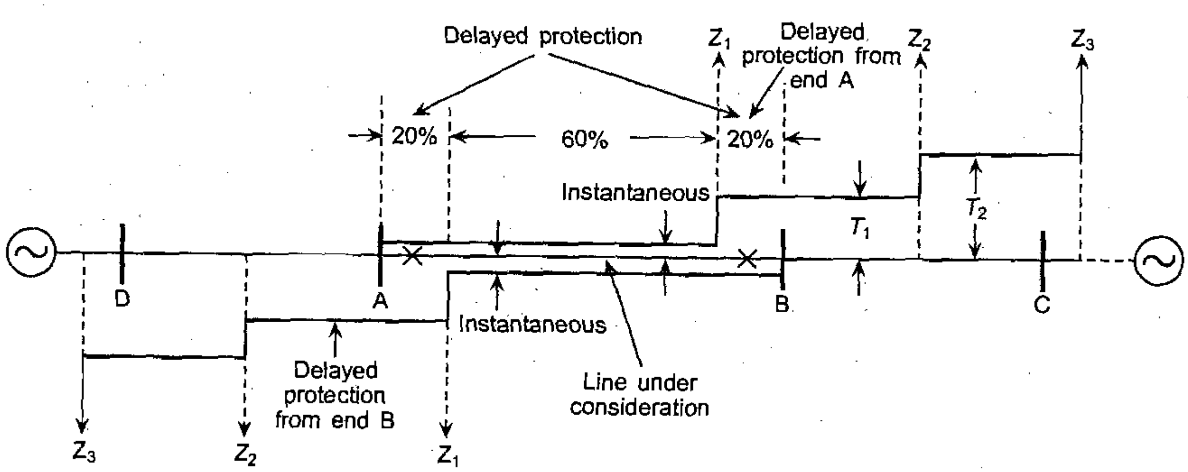

Figure 7.1 Only 60% of line length in the middle gets high speed protection from both ends.

7.2 Various Options for a Carrier

Protective relays process information contained in the voltage and current at the local end. The relay, only indirectly infers about the conditions at the remote end through these signals. As the fault distance increases, the picture becomes more and more fuzzy. Hence, there is always an ambiguity about the exact location of a remote fault. It becomes impossible to distinguish between a fault just beyond the remote bus and one just ahead of it. However, there is no ambiguity about the same fault from the end nearest to the fault because as the fault moves from just beyond the bus to just ahead of it, there is an almost 180 degrees change in the phase of current at the nearest end. Thus, the nearest end has the clear-cut information which is so difficult to extract using power, frequency, current and voltage at the remote end. If we could, somehow pass on this small amount of information from one end to the other, it would enhance the quality of decision making at both the ends. We, therefore, need some *carrier* to carry this information. Various attributes of an ideal carrier channel can be listed as follows:

- Delay involved in the communication should be small compared to the time period of the system frequency. At 50 Hz, the delay should be much less than 20 milliseconds.
- Since only a small amount of information is to be passed, the carrier channel need not have very high bandwidth for protection purposes.
- Faults on the power system should not adversely affect the functioning of the carrier channel.
- Carrier channel should be under full control of the utility company.
- The carrier equipment, such as carrier transmitter and receiver, should be protected from the high potential of the EHV line.
- The carrier channel should be economical.

Various available options for a carrier signal are listed, along with their salient features, in Table 7.3.

7.3 Coupling and Trapping the Carrier into the Desired Line Section

The power transmission line operates at very high voltage levels of the order of hundreds of kilovolts. The carrier signalling equipment, viz. the carrier current transmitter and the carrier current receiver, operate at a much lower voltage. Therefore, we need a method of coupling the two so that neither the high voltage line gets shorted through the carrier equipment nor does the signalling equipment get damaged due to the extra-high voltages of the power line. Figure 7.2 shows one such arrangement for coupling the carrier on a line-to-ground basis. *Line traps* which confine the carrier signal to the desired line section are also shown.

Table 7.3 Various possible carriers of information for relaying purposes

Leased telephone line from the telephone service provider	Running cost is very high. Maintenance is a problem and guarantee of quality of service may be difficult to obtain.
Terrestrial microwave communication channel (either owned by the utility or leased)	Frequency range is between 3 and 30 GHz. The range of communication is *line of sight*. A large number of antenna towers are required. Therefore, initial investment and maintenance cost are both very high. Provides very large bandwidth, which may be shared with other data communication services.
Satellite communication using VSAT terminals using geostationary satellite at 36,000 km	Frequency range is between 3 and 30 GHz. Propagation delays involved are of the order of (2)(36000) km/(3)$(10)^5$ km/s = 240 ms i.e. 12 cycles (50 Hz basis) and this is not permissible for real-time power system protection. Large bandwidth is available.
Power line carrier communication	Most economical, since power line conductor doubles as the physical medium for carrying the *carrier* signal. The carrier signal is a signal of much higher frequency, compared to power frequency, which is coupled to the EHV line. Frequency band allocated to this service is 50–200 kHz. Thus, the carrier signal frequency is just above the audible frequency range and just below the medium wave radio broadcast band. Due to moderately low frequency of the carrier, a small bandwidth is available. However, protective relaying does not need a large bandwidth. What is important is the delay involved, which is very small in case of power line carrier, for example, a 1000 km line will cause a delay of 0.33 milliseconds.

The impedance of the coupling capacitor is very large at 50 Hz compared to that of the parallel tuned circuit (which is tuned to carrier frequency) consisting of L_P and C_P. Therefore, the coupling capacitor drops most of the 50 Hz voltage so that a very small 50 Hz voltage appears across the signalling equipment. The series circuit consisting of C_S and L_S, as shown in Figure 7.2, is designed to resonate at the carrier frequency. Since the impedance of a series resonant *L-C* circuit is ideally zero, it provides very good coupling at the carrier frequency.

The parallel circuit consisting of L_P and C_P is tuned to resonance at the carrier frequency. Since the impedance of a parallel resonant circuit is ideally infinite at the resonant frequency, it develops maximum voltage at carrier frequency, thus helping to extract the maximum carrier signal.

The series and parallel *L-C* tuned circuits, therefore, help in efficiently coupling the carrier into the EHV line. The carrier signal, however, needs to be confined to the desired line section. The two line traps, which are parallel tuned *L-C* circuits, resonant at the carrier frequency, prevent the carrier signal from spreading into rest of the transmission system by virtue of their extremely high impedance at the carrier frequency. The line traps have to be so designed, however, that they do not offer any significant impedance at 50 Hz (power frequency). The line ends are thus clearly *demarcated* as far as the carrier signal is concerned. This clear-cut demarcation helps in establishing a well-defined zone whose boundaries are crisply defined.

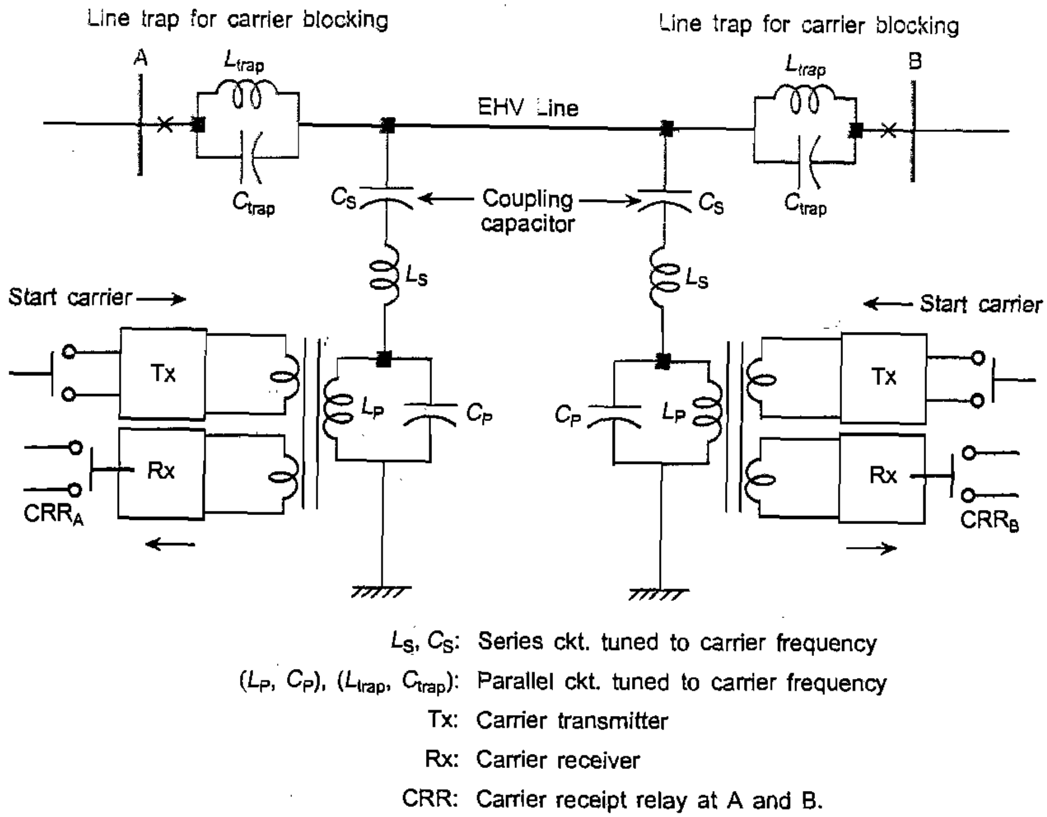

Figure 7.2 Coupling a carrier and trapping it into the desired line section (single line-to-ground coupling).

7.3.1 Single Line-to-ground Coupling

In Figure 7.2 we have shown carrier coupling on a single line-to-ground basis. Is this type of coupling, a wise choice?

Recall that, statistically, majority of faults are of the line-to-ground type. Further, in power line carrier communication, the information has to be passed over the power line itself. Therefore, during faults, when the carrier is needed the most, the carrier will have to be passed *across* the line-to-ground fault. This is bound to cause severe attenuation of the carrier signal, rendering it unusable at the remote end. Thus, line-to-ground coupling is not a very sound choice as far as carrier coupling is concerned.

7.3.2 Line-to-line Coupling

Figure 7.3 shows carrier coupling on the line-to-line basis. The carrier signals propagate through air between the line conductors, therefore, the attenuation is much less. This mode of transmission, known as the *aerial mode,* results in a much better performance during single line-to-ground faults.

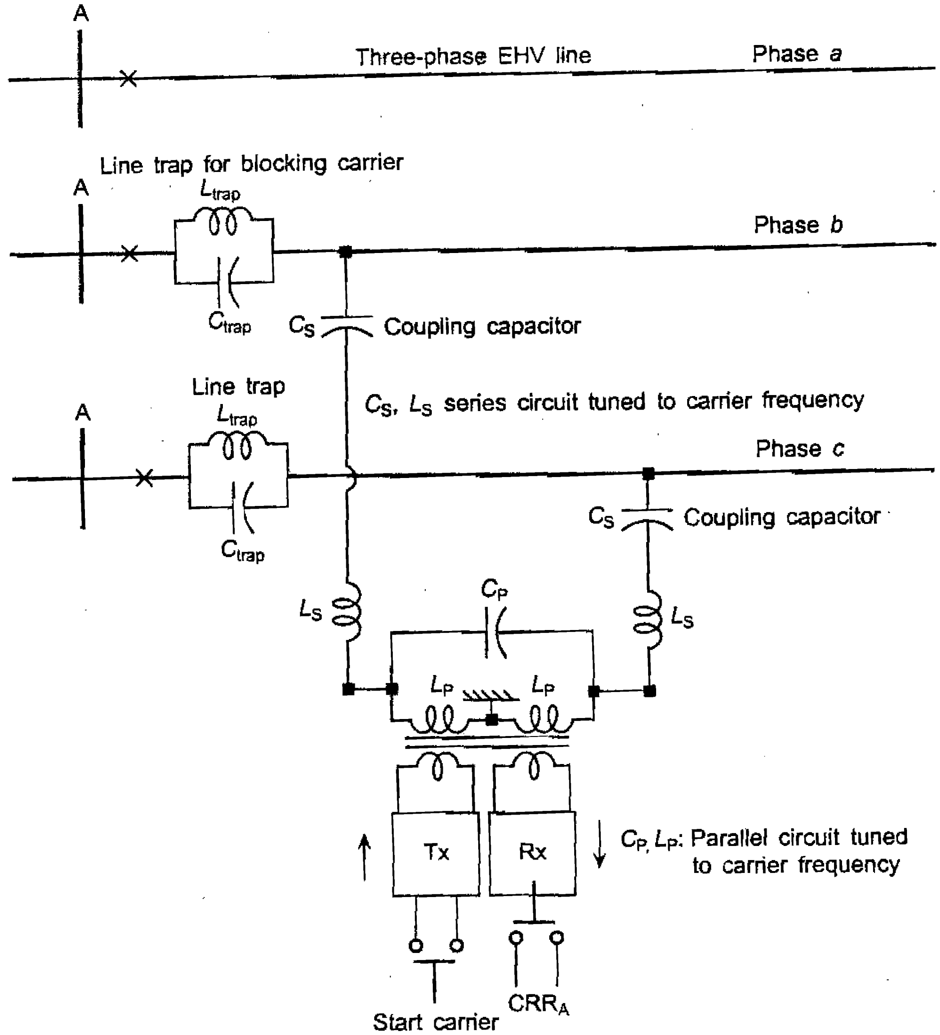

Figure 7.3 Line-to-line coupling.

7.4 Unit Type Carrier-aided Directional Comparison Relaying

This protection takes advantage of the fact that as the fault location changes from just ahead of the bus to just beyond the bus, the nearest directional relay sees a sharp change in the fault direction whereas the remote relay does not see any change in the direction of the fault. The remote relay cannot tell whether the fault is within the line zone or outside it whereas the nearest end relay has no difficulty at all in discriminating between the same. The information about the fault direction, as seen from each end, is conveyed over the power-line carrier to the other end. At each end, simply ANDing the contact of the local relay with the status of the contact of the remote relay gives rise to a unit type of directional protection.

Figure 7.4(a) shows an internal fault for which AND gates at both the ends become enabled and instantaneously trip the associated circuit breakers. This generates a well-defined zone of protection consisting of the line length between buses A and B.

Figure 7.4(b) shows an external fault. Since one input for each of the AND gates is low, both the AND gates are disabled, thus the unit scheme restrains on external faults.

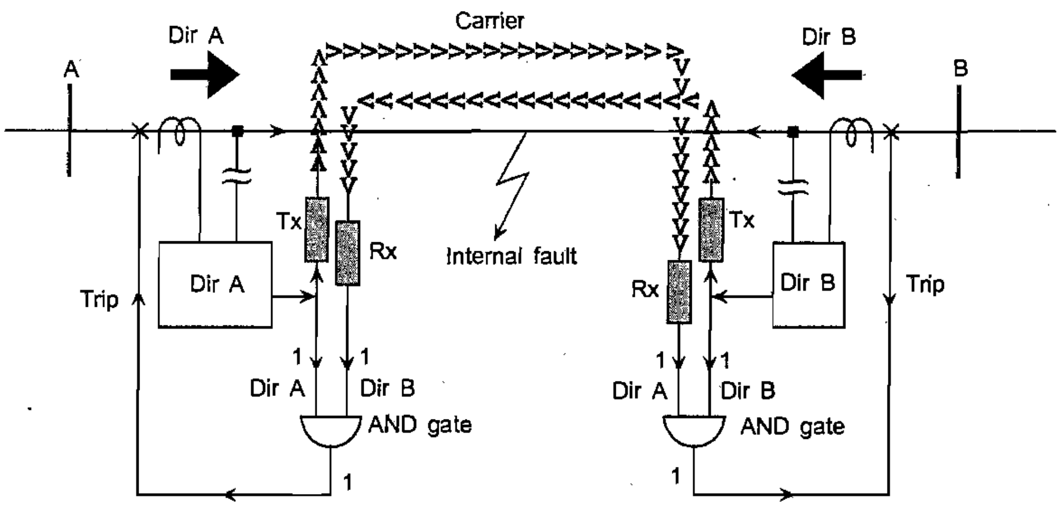

Figure 7.4(a) Unit type carrier-aided directional comparison relaying: internal fault.

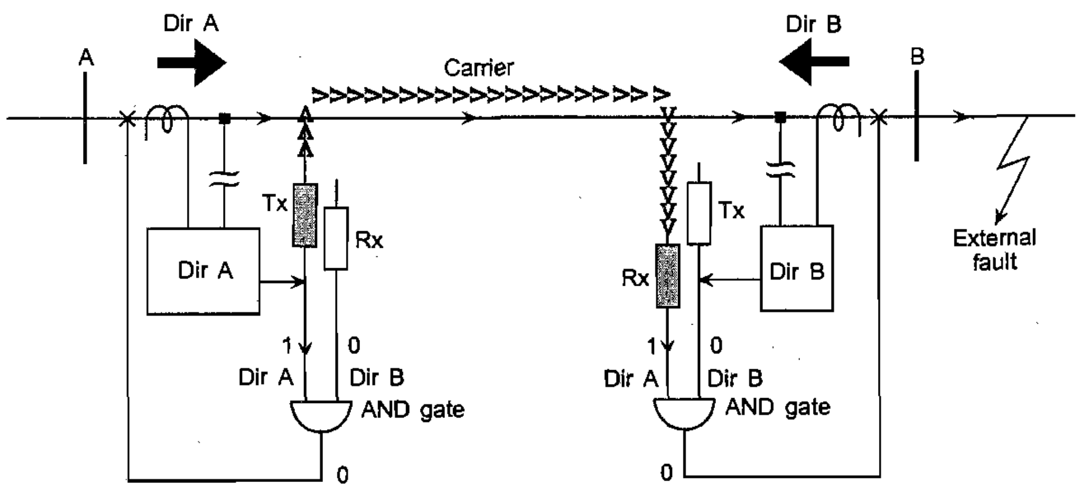

Figure 7.4(b) Unit type carrier-aided directional comparison relaying: external fault.

There is absolute selectivity as far as the ends of the zone are concerned, giving rise to a well-defined protective zone, hence this scheme is classified as a *unit type* of protection. Both the relays use the directional principle, hence it is called *unit type directional* protection.

7.5 Carrier-aided Distance Schemes for Acceleration of Zone II

7.5.1 Transfer Trip or Inter-trip

As mentioned earlier, the faults in the end 40% (20% on each side) of the transmission line fall in the second step of distance protection. It is, therefore, a delayed protection. Thus, only about 60% of the mid-length of the line, gets high-speed distance protection. For faults in the end 40%, the nearest distance protection trips instantaneously but the remote end protection is a delayed one. How to speed up the remote end distance protection?

Consider a fault in the second zone of distance protection, but not beyond end B, as seen from end A. We can make use of the first zone, Z_1 contact of the local relay at end B, to initiate a carrier and thus remotely operate a contact to close the trip circuit of the remote circuit breaker at end A. The logic of this scheme is shown in Figure 7.5. The logic can be understood by following the Roman numerals written in parentheses as follows:

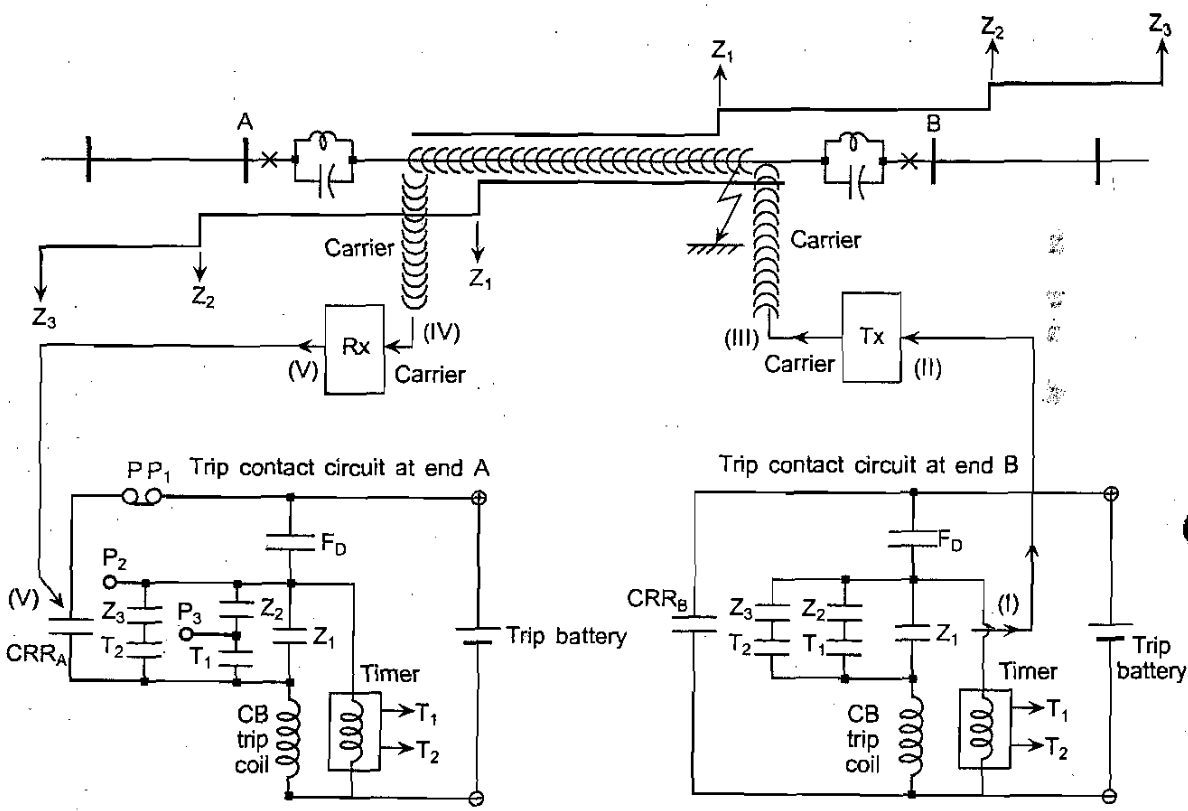

Figure 7.5 Acceleration of zone II of distance relay using carrier.

(I) Z_1 contact of the local relay at end B operates (NO → CLOSES).

(II) This contact closure is used to switch on the carrier transmitter at end B, marked as Tx in the figure.

(III) The carrier transmitter injects the carrier into the line.

(IV) The carrier signal arrives at the remote end A at approximately the speed of light, after a very short delay, and is received by the carrier current receiver, marked as Rx.

(V) The output of the receiver (Carrier Receipt Relay, at end A, designated as CRR_A) is in the form of closure of the contact CRR_A.

Now, the CRR_A contact can be used to energize the trip coil of the circuit breaker at remote end A in several alternative ways.

If we bypass the fault detector F_D contact by connecting point P with P_1, then the scheme is known as *transfer trip* or *inter-trip*.

In this scheme, the carrier signal is required for tripping purposes. Therefore, in case of either the failure of carrier equipment or severe attenuation of the carrier signal due to fault, the operation of the scheme is jeopardized. Thus a tripping carrier scheme lacks robustness. Ideally, the carrier-based scheme should be such that in case of failure of carrier, it should automatically revert back to the three-stepped distance scheme. The logic can be built in such a way that the carrier signal is not required for tripping but is required for blocking the tripping. Such schemes are obviously more robust and are known as *blocking carrier* schemes.

7.5.2 Permissive Inter-trip

At times, noise may cause false tripping in the scheme described in Section 7.5.1. Therefore, we can take advantage of the fault detector output. Hence if point P, in Figure 7.5 is connected to point P_2 then the scheme is known as *permissive inter-trip*.

7.5.3 Acceleration of Zone II

Alternatively we can simply bypass the zone II timer contact T_2, in Figure 7.5, with CRR_A, in which case the scheme is known as *acceleration of zone II*.

7.5.4 Pre-acceleration of Zone II

In this scheme, the zone II timing is accelerated from T_1 to a much smaller value. This is done by shorting out the T_1 contact of the timer (which controls Z_2 timing), with the normally closed output of carrier receipt relay at end A, CRR_A, as shown in Figure 7.6. In case the fault is beyond the bus, the directional relay sees the fault and initiates a carrier. The carrier is now sent over a line section which is healthy (on which there is no fault). On receipt of the carrier at end A, the carrier receipt relay changes state from CLOSE to OPEN. Thus T_1 contact now comes into picture and decides the operating time of zone II. The sequence of events can be easily understood, if one follows the Roman numerals written in parentheses in Figure 7.6.

(I) Fault takes place beyond the bus, in zone II, as seen from end A.

(II) Directional relay at end B senses the fault and instantaneously issues the trip output.

(III) The trip output of directional relay is used to start the carrier transmitter at end B.

(IV) The carrier transmitter at end B sends the carrier over the healthy power line.

(V) The carrier is received at end A, after a brief propagation delay, by the carrier receiver.

(VI) Carrier receiver issues an output, CRR_A, in the form of a changeover of contact from CLOSE to OPEN.

(VII) This output is used in parallel with the T_1 contact to de-accelerate the zone II time which was pre-accelerated with the help of NC contact of CRR_A.

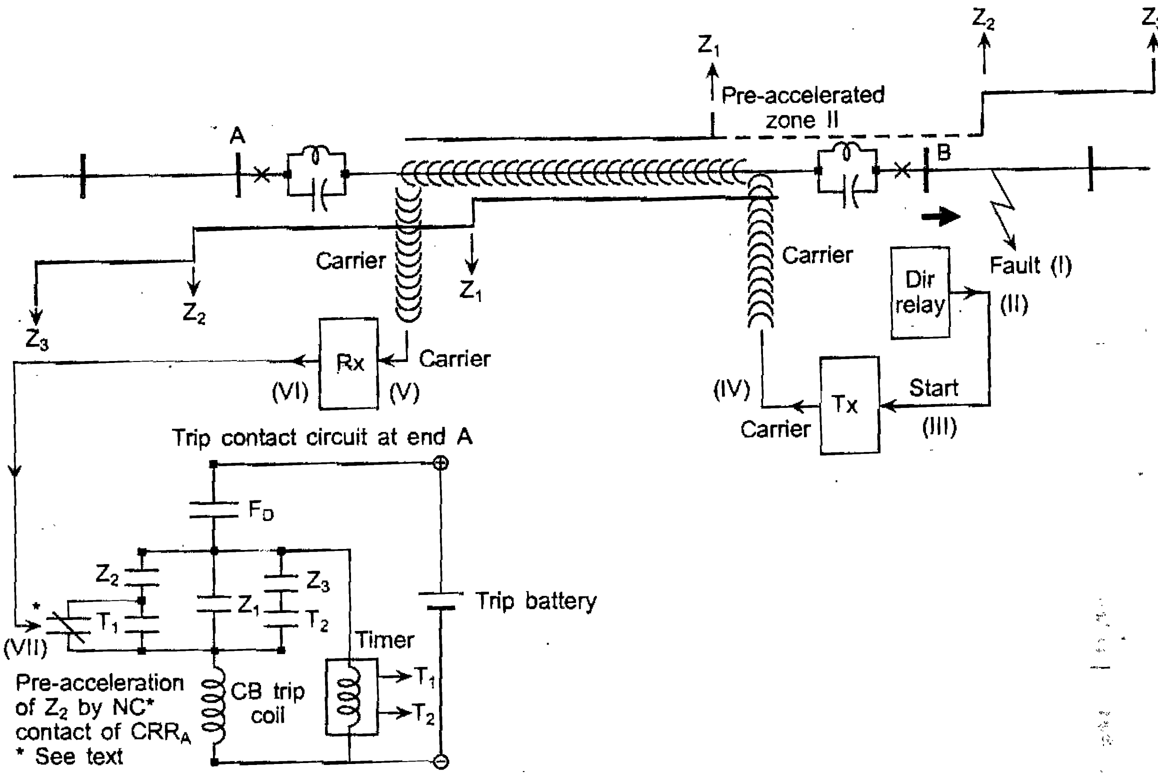

Figure 7.6 Pre-acceleration of zone II.

This has been a rather idealistic discussion of the operation of the system. In actual practice, Z_2 operation should not be made instantaneous. If Z_2 is made instantaneous then it will not give chance to the directional relay to operate and de-accelerate the Z_2 time, in case, the fault is beyond the bus. We have to allow for the following delays:

1. Operating time of directional relay T_{dir}
2. Propagation time of carrier over the length of the line T_{prop}
3. Operating time of the carrier receiver T_{CRR_A}

Thus, zone II should be pre-accelerated to an operating time of:

$$T_{\text{pre-accelerated}} \geq T_{dir} + T_{prop} + T_{CRR_A}$$

This is, however, not shown in the figure.

It can be seen that the carrier is required for blocking the instantaneous operation of the pre-accelerated zone. This is an example of a *blocking carrier*.

7.6 Phase Comparison Relaying (Unit Scheme)

In this type of relaying, we exploit the phase shift undergone by the current at the end which is nearest to the fault, as the fault changes from internal to external. The end, which is far from the fault, cannot discern any change in the phase of the fault current as the fault changes from internal to external but the end which is closer to the fault sees a sharp, almost 180° change in the phase of current.

The local and remote end currents can be arranged to be out of phase for external fault or load condition as shown in Figure 7.7(a). This can be achieved by selecting the appropriate end of the CT winding as the reference. The phase shift will, however, not be exactly 180°, but may lag or lead this position by a small angle $\pm\delta$ representing the load being carried over the line.

As the fault changes from an external fault to an internal one, the current at the nearest end will undergo an approximately 180° change in its phase and will now be more or less in phase with the remote end current as shown in Figure 7.7(b). Thus, if we measure the phase shift between the currents at the two ends, then we can easily decide whether the fault is internal or external.

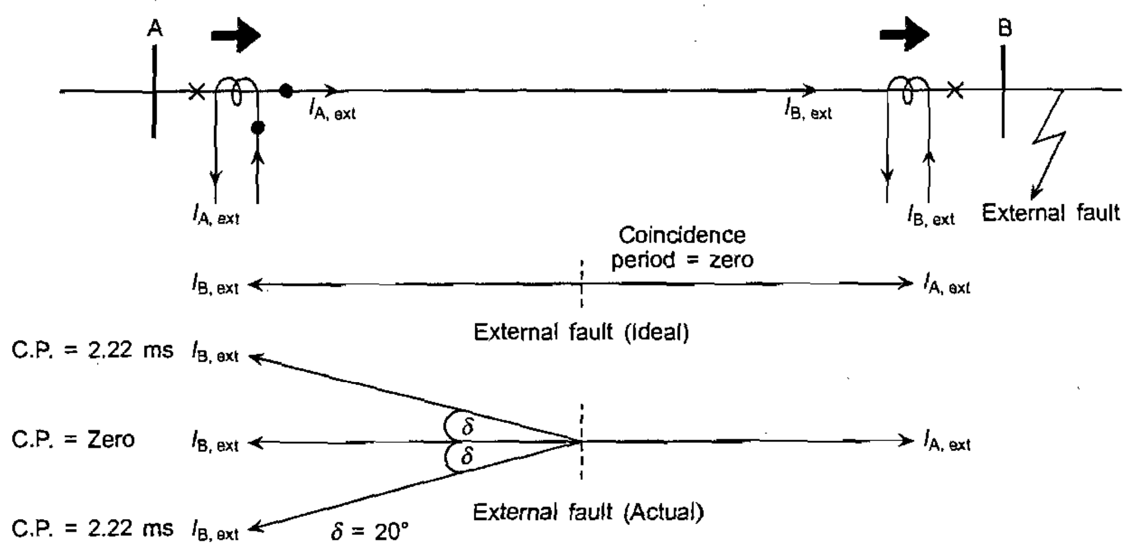

Figure 7.7(a) Phase comparison relaying (currents shown on the CT secondary side).

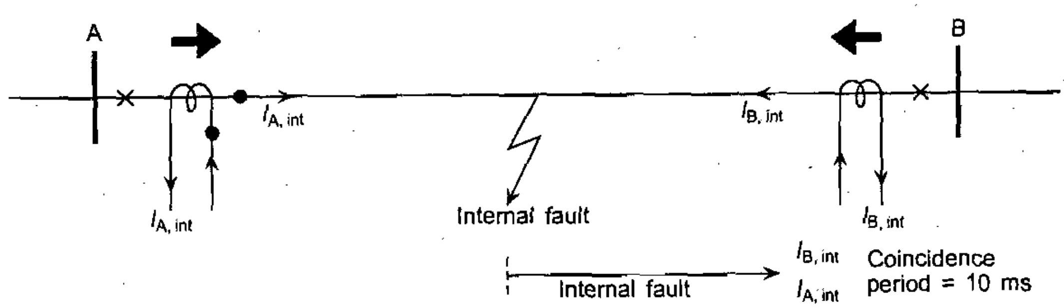

Figure 7.7(b) Phase comparison relaying.

Assuming δ to be, say, 20° then any phase shift between 0 and ±160° will indicate an internal fault, as shown in Figure 7.7(c). A phase shift of $\pm\delta$ gives rise to a coincidence period C.P. of

$$\frac{(180 - \delta)(20)}{180} = 2.22 \text{ ms}$$

for phase shift of ±160°.

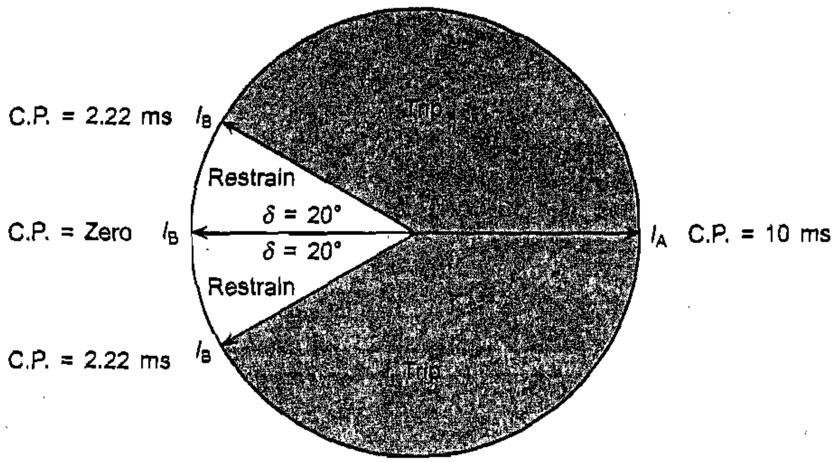

Figure 7.7(c) Phase comparison relaying.

Figures 7.7(d), (e), and (f) show a method for physical implementation of the above mentioned concept.

Figure 7.7(d) shows an internal fault. As shown in the figure, each end periodically sends carrier only during the positive-half of the time period of the power frequency ac wave. This results in generation of a modulated carrier wave. This modulation can be easily recovered back by demodulation to get a square waveform at the output. For an internal fault, the figure shows that the demodulated square waves are exactly coincidental. The coincidence period, thus, is 10 ms (on a 50 Hz basis).

Figure 7.7(e) shows an external fault. Again the two ends generate carrier only during the positive-half of the power frequency wave, generating similar modulated waves. However, because of the phase shift, now, the demodulated square waves do not have any coincidence at all or the coincidence period is nearly zero.

The coincidence period can be easily found by ANDing the two demodulated waves. To see if the coincidence period is greater than a certain threshold, we can either use any digital method or follow the simple expedient of integrating the square wave and comparing it with a preset dc value which represents the desired threshold, as shown in Figure 7.7(e).

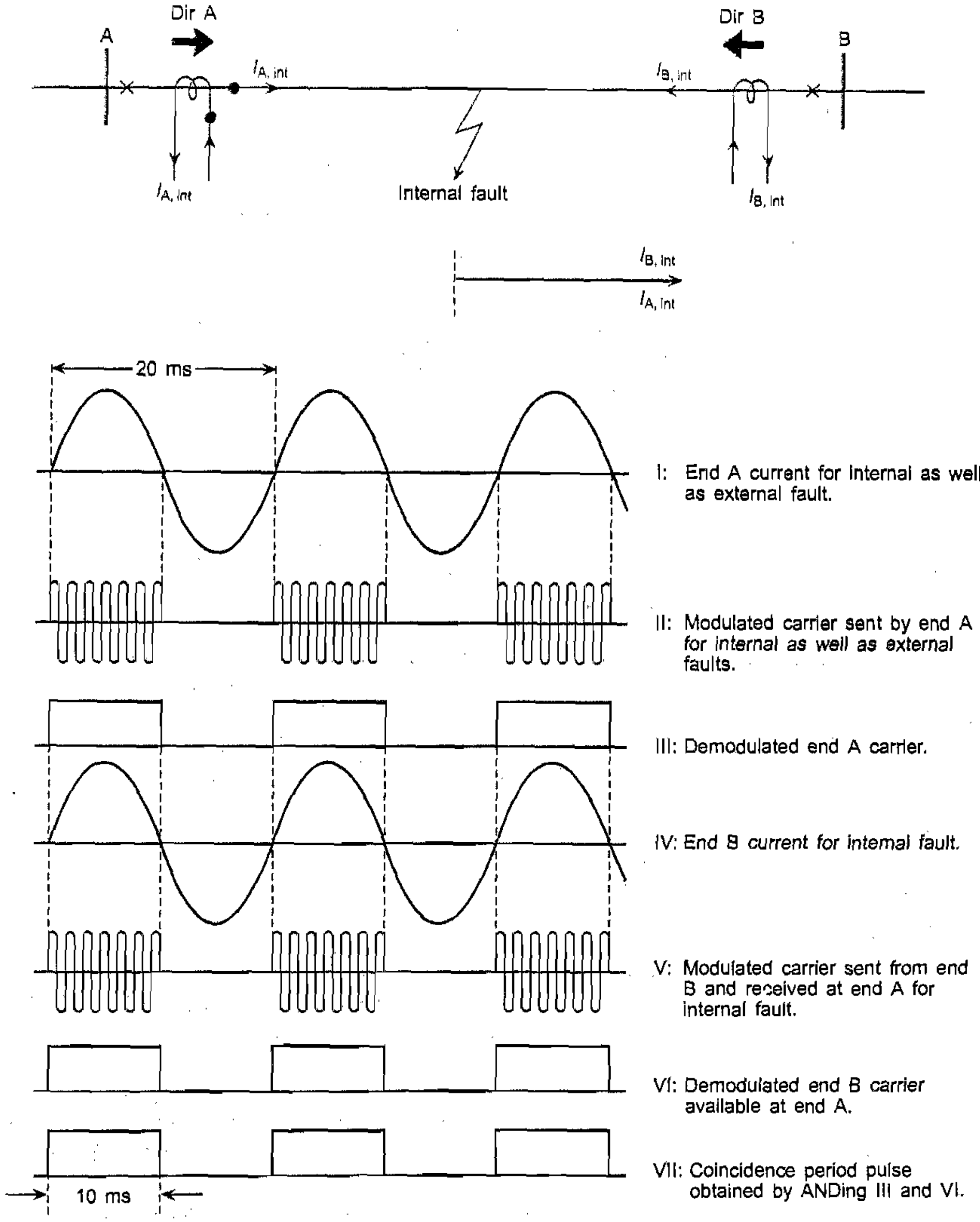

Figure 7.7(d) Phase comparison relaying (internal fault).

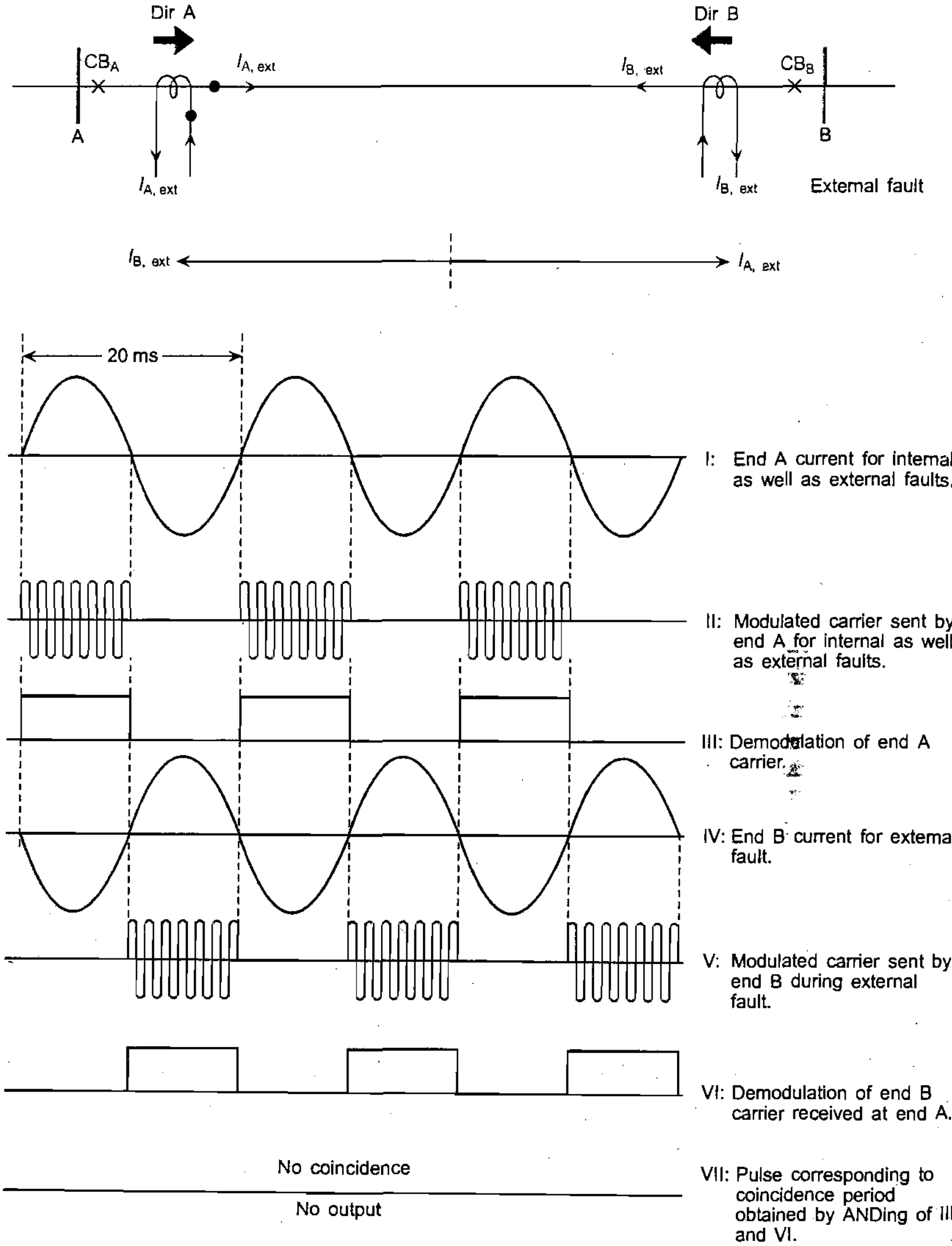

Figure 7.7(e) Phase comparison relaying (external fault).

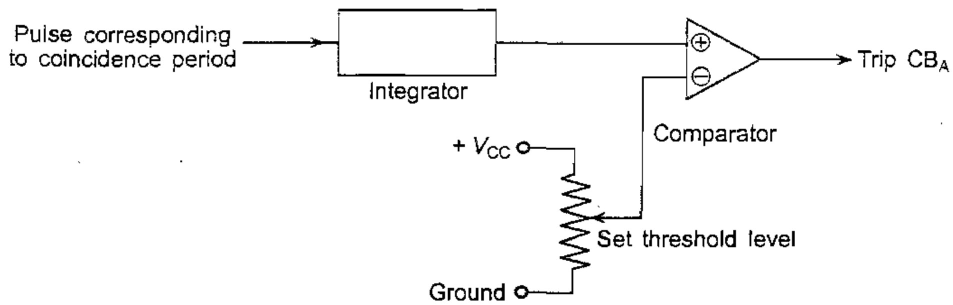

Figure 7.7(f) Hardware to measure coincidence period.

Review Questions

1. What do you mean by reclosure?
2. What is the motivation for using reclosure?
3. Differentiate between reclosure in case of low-voltage systems and high-voltage systems.
4. What is meant by single-shot reclosure and multi-shot reclosure?
5. What is the motivation for using a carrier?
6. What are the various options for implementing the carrier communication channel?
7. What are the advantages of power line carrier?
8. What frequency band is normally used for power line carrier signalling?
9. What is the frequency band used for microwave communication?
10. What is the motivation for coupling the carrier between two of the lines rather than between a line and ground? Which method results in more reliable carrier communication?
11. Explain why only middle 60% of the double-end-fed line gets instantaneous distance protection from both ends in a three-stepped distance scheme.
12. How does the carrier help in overcoming the limitation of the three-stepped distance protection?
13. Explain the difference between transfer trip and permissive inter-trip schemes. Which scheme is more robust?
14. How does the carrier-based acceleration of zone II differ from the transfer trip and permissive inter-trip schemes?
15. Why does sending the carrier over a faulty line need to be avoided?
16. What do you mean by tripping carrier and blocking carrier? Which one is more robust?
17. What do you mean by pre-acceleration of zone II?
18. In practice, the zone II cannot be pre-accelerated to an instantaneous operation. Explain.
19. Explain the operation of the unit type of carrier-based directional protection.
20. Explain the principle of carrier-based phase comparison scheme.