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During any stage of evolution of a power system, there will be some combination of operating conditions, faults or other disturbances which may cause the loss of synchronism between areas within the power system or between interconnected systems. If such loss of synchronism can or does occur, it is imperative that the asynchronous areas be separated before equipment is damaged or before a widespread outage can occur.

System separation because of instability should not be a random procedure. Ideally, the system should be separated at such points as to maintain a balance between load and generation in each separated area. Moreover, separation should be performed quickly and automatically in order to minimize the disturbance to the system and to maintain maximum service continuity.

Over the years, a number of protective relays and schemes have been developed to detect a loss of synchronism and to perform the necessary functions to preserve the system. This equipment falls into two general categories: out-of-step blocking relaying and out-of-step tripping relaying. It is the purpose of this paper to describe the relays and schemes available to provide these functions and discuss their application on present-day power systems.

LOSS OF SYNCHRONISM CHARACTERISTIC

Before considering the out-of-step relaying equipment and its application, it would be appropriate to review briefly the characteristic of a loss of synchronism condition.

When two areas of power system or two interconnected systems lose synchronism, there will be large variations in voltages and currents throughout the systems. The voltages will be maximum and the currents minimum when the systems are in phase and the voltages will be minimum and currents maximum when the systems are 180 degrees out of phase. This fluctuation in voltage and current could be used to detect a loss of synchronism but it may take several slip cycles to determine they were due to an actual loss of synchronism.

A more convenient and faster method for visualizing and detecting loss of synchronism is to use the ratio of voltage to current or impedance. It has been shown 1, 2, 3 that during a loss of synchronism, the impedance as seen at a line terminal, will vary as a function of the angular separation between the systems. This variation in impedance can readily be detected and the systems separated before the completion of one slip cycle.

To illustrate this impedance loss of synchronism characteristic, consider the simplified system diagram of Fig. 1, where a section of transmission line is shown interconnecting two generating sources. The sources may be actual generators or equivalent systems representing a group of generators that will remain in synchronism with respect to each other. In this simplified approach for determining a loss of synchronism characteristic, the following assumptions are made: initial transients (D-C or 60 Hz components) and effects of generator saliency are neglected; transient changes in impedance due to a fault or clearing of a fault (or due to any other disturbance) have subsided; effects of shunt loads and shunt capacitance are neglected, effect of regulators and governors are neglected; the voltages E_A and E_B behind the equivalent impedances are balanced sinusoidal voltages of fundamental frequency; and the ratio of the voltages E_A/E_B remains constant.

If system B, (E_B), is taken as a reference and it is assumed E_A will advance in phase angle ahead of E_B, reference 1 shows that the impedance as seen by terminal C during a loss of synchronism will be

$$Z_R = (Z_A + Z_L + Z_B)n\,\frac{(n-\cos\delta) - j\sin\delta}{(n - \cos\delta)^2 + \sin^2\delta} - Z_A$$

where

Z_A, Z_B, Z_L = system and line impedances
δ = angular separation between E_A and E_B
n = Ratio E_A/E_B

This is a general equation for the loss of synchronism characteristic. If a value for (n) is assumed and the angle (δ) varied between 0 and 360 degrees, an impedance focus will be obtained which can be plotted on the R-X diagram. For example, if it is assumed that n = 1 and that (δ) is varied over a finite range,the impedance locus or loss of synchronism characteristic is as shown in Fig. 2. This locus is a straight line PQ which is the perpendicular bisector of the total system impedance between A and B. On this diagram, the angle formed by the intersection of lines AP and BP on line PQ is the angle of separation (δ) between the systems. As source A moves ahead of B in angle, the locus moves from point P toward Q, the angle δ increases and the impedance as seen at 7(Z_R) is as shown on the diagram. There are several points of interest along this locus. The first is the point where δ = 90 Degrees. This point lies on the circle whose diameter is the total impedance line AB and is the point corresponding to maximum load transfer between A and B. If the swing locus does not go beyond this point the systems will most linely recover and remain stable. On the other hand, if the locus reaches 120 degrees and goes beyond, the systems are not likely to recover; that is, stability is likely to be lost.

When the locus intersects the total impedance line AB, the systems are 180 degrees out of phase. This point is called the electrical center or impedance center of the system. As the locus moves to the left of the system impedance line, the angular separation increases beyond 180 degrees, and eventually the systems will reach the point where they will be in phase again. If the systems are not separated, system A will continue to move ahead of B again and the whole cycle repeats itself. When the locus reaches the point where the swing started, say at δ = 45 Degrees, one slip cycle has been completed.

The rate of slip between the two systems is a function of the accelerating torque and inertias of the systems. In general, the slip can not be determined analytically but it can be obtained from transient stability studies where angular excursions of the systems are plotted versus time. From these plots, an average slip in either degrees/sec or cycles/sec can be determined. The slip between the systems will not be constant. However, the general practice is to assume a constant slip for the portion of the first slip cycle which is of interest; namely, the starting point of the swing locus and the point of 180 degrees separation between systems.

If (n) is greater or less than one (1), the loss of synchronism characteristics will be circles with their centers on extensions of the total impedance line AB. These characteristics are shown in Fig. 3. These circles can be determined graphically by using the simple expressions for locating the center of circles and the radii as shown in Fig. 3. The ratio of the voltages (n) can also be determined graphically, if the initial load transfer from A to B is known. This load transfer can be represented by an impedance point P. The ratio of line lengths AP/BP is equal to (n). The load point P will fall on the loss of synchronism characteristic and will be the starting point of the impedance locus.

For most purposes, it is not necessary to go to the refinement of plotting the loss of synchronism characteristics of Fig. 3. In most cases, it is sufficient to assume a voltage ratio of n = 1 and simply draw a perpendicular bisector to the total impedance line as in Fig. 2. This will usually locate the point on the system where the swing will traverse with sufficient accuracy for relaying purposes.

In the above discussion, it was assumed that the system could be represented by a transmission line interconnecting two generating sources. Quite often, a complicated system can not be so represented, in which case the swing or out of step loci would have to be obtained by means of a digital or analog study.

It should also be noted that the electrical center of the system is not a fixed point. The location of this center will vary as the system impedances behind the line terminals vary. Therfore, when determining the loss of synchronism characteristic as seen at a line terminal, it will be necessary to consider changes in system conditions (that is, variations in Z_A and Z_B of Fig. 1) and determine a locus for each condition.

EFFECT OF LOSS OF SYNCHRONISM ON SYSTEM RELAYS

A loss of synchronism between systems will affect the relaying on these systems in various ways. Some relaying such as differential relaying will not respond to a loss of synchronism while others such as overcurrent, directional and distance relays may detect an out-ofstep swing and therefore may operate to trip their breakers. Since an out-of-step condition is a balanced three-phase phenomenon, the primary concern is the effect of the swing on phase relaying. However, if there are impedance dissymmetries on the system it may be possible to have operation of sensitively set overcurrent ground relays during swings.

Effect on Differential Relays

Current differential relaying used for the protection of generators, transformers, buses and lines (such as pilot wire relays and phase comparision) will not be affected by an out-of-step swing. During a loss of synchronism between systems A and B of Fig. 1 where A swings ahead of B, there will be a current flow for A to B. This will be a "through" current and therefore, the swing would appear as an external fault condition to a current differential scheme. If a swing locus happens to go through a bus, a transformer or a line which has pilot wire or phase comparison relaying and if system separation is desired at the point, some other form of relaying either for back-up or supplementary, will have to be provided to detect the swing.

Effect on Overcurrent Relays

It should be obvious that overcurrent and directional overcurrent relays used for phase fault protection will operate if the "swing" currents exceed the pickup settings of these relays. In fact one of the shortcomings of this type of relaying is that they may operate during swings from which the system may recover and remain stable.

Effect of Distance Relaying Schemes

Any distance relay which measures positive sequence impedance during three-phase faults will operate if the swing locus enters its operating characteristic. Whether the relay will actually complete its operation and trip its breaker depends on the distance relay zone involved and the length of time it takes for the swing locus to traverse the relay characteristic. In general, only the distance relay backup time step is likely to involve enough time delay to prevent tripping during a swing.

The performance of distance relays during swings is dependent to some extent on the relative magnitudes of system and line impedances. For instance, if the line impedance is small with respect to the system impedances, it is likely the various distance relay zones will trip only on swings from which the system will not recover. This situation is illustrated for terminal C in Fig. 4. As shown in this diagram, the swing locus will enter the distance relay characteristics only when the angular difference between systems is greater then 120 degrees. In this case, tripping may be provided by any of the three zones. If the slip between the systems is slow and if the time settings of the second and third zones are low, it is possible that either the second or the third zone relays or both may operate during the swing. If these two zones do not operate, the first zone will certainly operate when the locus enters its characteristic. While not shown, terminal D will have a similar set of relays as at C. If the line is short (less than 150 miles in length), the relays at D will see the same swing locus and therefore would perform in the same manner as the relays at C. If the line is long, the shunt capacitance of the line will have an effect and the swing locus as seen at C and D will not be the same. For instance, on lines 200-300 miles in length, the-loci may be similar to the n> 1 and n < 1 circles as shown in Fig. 3. Terminal C would see the n < 1 locus while D would see the n > 1 locus. In any event, the relays at C and D would still see the swing and would operate to separate the systems.

To illustrate the method for determining whether or not a time delay zone will operate during a swing, consider the example in Fig. 5. In this case, it is assumed that n is greater than (1) and that the swing will only go through the third zone characteristic. This diagram gives the expression for determining the time it will take for the locus to traverse the relay characteristic. The distance traveled by the locus is obtained in degrees(δ_2 - δ_1) and the slip S, is in degrees per second. If the time (t) is greater than the thrid zone time setting, the relay will operate and trip its breaker. If the R-X diagram is drawn to scale, the distance traveled by the swing locus can be obtained by measuring the angles δ_1 and δ_2 with a protractor.

In contrast to the above example, if the line impedance is large as compared to the system impedances, the distance relay zones may not only trip during unstable swings but may also trip on swings from which the system can recover. This situation is illustrated in Fig. 6. For purposes of clarity, only two zones of protection are shown. In this case, the second zone relay will see the swing before the systems are 90 degrees apart while the first zone relay will see the swing before the systems are 90 degrees apart while the first zone relay will see the swing before 120 degrees of separation is reached. In both cases, the relays could trip for swings from which the system could recover. In this instance, either some method of blocking such tripping will have to be provided or if it desired to permit tripping, the tripping area covered by the line relay characteristics must be restricted. Several means for restricting the tripping area, such as the use of blinders, are discussed in reference 4.

While the above discussion has used straight distance relaying to illustrate the effect of swings, the comments also apply to the directional comparison or any of the transfer trip schemes. These comments also apply to ground distance relays since these units can also see load current or positive sequence impedance during three phase faults. In some instances these units will be prevented from tripping incorrectly during swings by the zero sequence overcurrent fault detectors normally provided with the ground distance relaying schemes. However, if there is a circulating zero sequence current during swings, and it is not possible to set these fault detectors to prevent such tripping, supplementary blocking relays wili have to be provided. This blocking equipment will be discussed in the next section.

OUT-OF-STEP RELAYING EQUIPMENT

There are two basic types of euqipments used in out-of-step relaying. These are out-of-step blocking relays and out-of-step tripping relays. Since an out-of-step condition is a balanced three-phase phenomenon, these relays are, and need, be only single phase devices. Each of these equipments will be discussed separately.

Out-Of-Slep Blocking Relays (Electromechanical)

The standard relay used for out-of-step blocking is an offset mho unit type CEB12B. This unit operates in conjunction with mho-type tripping units used for line protection to provide either blocking of tripping during severe swings and out-of-step conditions or blocking of automatic reclosing after an out-of-step trip by the line relays. In whichever function it is used the operation of this scheme is the same.

Figure 7 illustrates how out-of-step blocking is accomplished. The out-of-step blocking unit characteristic is set so that it is larger than and concentric with the line tripping relay characteristic. During a swing, the impedance locus moves toward the relay characteristics and enters the out-of-step blocking unit circle at A. A short time later, it reaches point B and enters the tripping circle. If the transit time of the locus between points A and B exceeds a few cycles, the out-of-step blocking unit will operate an auxiliary device which will block the line relays if blocking of tripping is desired at that point. If blocking of reclosing is desired, the line relays would be permitted to trip and the auxiliary device would incapacitate the automatic reclosing equipment.

The operation of this out-of-step blocking scheme is based on the fact that there is a progressive change in impedance as viewed by the relay units and not an instantaneous change as would occur during a fault. For instance, if a fault occurs at point C, there would be an instantaneous change of impedance from P to C. Both the tripping and'out-of-step blocking units will operate for this condition, but the tripping units will incapacitate the blocking auxiliary unit before it can set up blocking.

On three terminal lines where sequential tripping is used, this standard out-of-step blocking unit may not be applicable because it may block tripping incorrectly for internal faults.[4] A modified form of the above out-ofstep blocking relay is available to take care of this contingency. This relay type CEB14 has a modified reactance relay included in the scheme and its characteristic is shown in Fig. 8. Out-of-step blocking is restricted to the shaded area. The use of this relay will be discussed in the Applications section.

Out-of-step blocking can also be obtained with an impedance relay type CFZ17 when this type of unit is used to start carrier in a directional comparison carrier current scheme. This approach is shown in Fig. 9 and it operates in the same manner as the off-set mho blocking relay. That is, blocking is set up when the transit time of the swing locus exceeds a few cycles as it travels from the impedance circle to the mho tripping circle. This scheme may also cause incorrect blocking when used on a three terminal line.

Out-of-Step Tripping Relay (Electromechanical)

The out-of-step tripping relay type CEX 17 consists of two modified reactance type units whose characteristics are shown as lines A and B in Fig. 10. These characteristics are straight lines which can be adjusted to be approximately parallel to the system impedance line.

When a loss of synchronism occurs, the swing locus (assumed to start at P) will eventually enter the area between the relay characteristics and emerge to the left of relay A. This sequence of events will be recognized by the relays A and B and will be "evaluated" by associated auxiliary relays to ascertain that a loss of synchronism has occurred. These relays will then either trip the local line breaker or initiate a transfer trip signal if tripping is desired at some other location.[5] Tripping will occur after the swing locus passes point X'. This scheme will recognize and trip for a loss of synchronism condition when the swing locus proceeds from P to Q or when it comes from the opposite direction from Q to P. Furthermore, this scheme will detect a swing behind the relay terminal, (E) (locus P'Q' Fig. 10) as well as in front of the terminal.

A simple instantaneous overcurrent unit is provided to supervise the operation of the scheme. The purpose of this overcurrent unit is to prevent tripping by the modified reactance relays during a light load condition when there is little power flow and therefore almost zero angle between systems. The zero degree point lies on the extension of the system impedance line (CD) somewhere above point D and will fall within the area covered by the modified reactance relays A and B. During this light load condition, the power flow between systems could be quite erratic in direction (although small in magnitude) and the modified reactance relays would see an erratic variation in impedance which may cause operation of these units. The overcurrent relay is set so that tripping will only occur when the swing currents are at least of the same order of magnitude as load currents.

Static Out-of-Step Blocking and Tripping Relays

Static relays and logic circuitry provide a means for obtaining desirable relay operating characteristics and greater flexibility in the out-of-step relaying function. With static relaying equipment, it is possible to obtain the following functions in one package:

1. Out-of-step blocking of tripping or of automatic reclosing.
2. Out-of-step tripping for unstable swings.

The relay characteristics and logic circuitry for this versatile scheme are shown in Fig. 11.

Figures 11A and 11B show the relay characteristics available to perform the out-of-step relaying functions. The characteristic of Fig. 11A is the same offset mho unit described earlier and as before it would be set to be larger than and concentric with a mho tripping unit. Figure 11 B illustrates a lens characteristic which would be used in those applications where a restricted operating area is required. In this scheme, a lens unit (LT), which is non-directional, would supervise tripping of a directional mho unit (MT). Tripping is restricted to the shaded area. The out-of-step function is obtained with another lens unit, LOB, which would be set larger than and concentric with the (LT) lens unit.

The out-of-step blocking function is obtained in much the same manner as in the electromechanical schemes. That is, blocking of tripping or recloging is set up when the transit time of the swing locus exceeds a few cycles as it travels from the MOB unit to the MT unit of Fig. 1 1A or from the LOB unit to the LT unit of Fig. 11 B. The logic train for this function appears in the upper half of the logic diagram of Fig. 11 C. Out-of-step blocking would be established as follows: When an output appears from MOB or LOB, and no output from MT or LT, AND1 will produce an input to the A/16 timer. "A" milliseconds later, the timer produces an output which can be used to block carrier tripping or block second zone tripping or block reclosing depending on the selection of the link settings. The pick-up time "A" is adjustable between 2-4 cycles (32 to 64 milliseconds).

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In addition to the out-of-step blocking function, the same complement of relays can provide out-of-step tripping. The logic for this function is in the lower half of the logic diagram of Fig. 1 1C. Functionally, this scheme will initiate tripping when a swing enters the trip relay characteristic (Mt or LT) and then sometime later passes back out on either side of the MOB or LOB characteristic. The logic train shown in Fig. 11C recognizes this swing and initiates tripping when the following sequence of events occur:

1. MT or LT picks up more than "A" milliseconds later than MOB or LOB.
2. MOB or LOB drops out one (1) cycle or longer after MT or LT drops out.

This sequence establishes that there is a progressive change in impedance as viewed by the relay units and not an instantaneous change as would occur during a characteristic to the blinder characteristic. In most cases, the use of blinders will permit reasonable OSB relay settings and will provide greater flexibility in choice of blocking functions.

It was mentioned earlier that the standard offset mho OSB relay and the impedance relay (Fig. 9) could cause incorrect blocking on a three terminal line. The problem and relay characteristic are illustrated in Fig. 13. In this illustration, if terminal A is relatively weak as compared to terminal B, it may be impossible to set the carrier trip relays at A to see a fault at C, because the required relay reach would be so large that the relay might trip on load or minor swings. In such situations, the relays at A would be set to see the fault at C with terminal B open and high-speed sequential tripping would be accepted when terminal B is in service. With this trip relay setting and with out-of-step blocking at A, it may be possible to incorrectly block terminal A for the fault near C. For instance, with maximum infeed at B, the apparent fault impedance seen by A may be at C' as shown in Fig. 13B. Under this condition there would be no problem. While A can not see the fault initially, it will see the fault after B trips and high-speed sequential tripping will occur. On the other hand, if infeed at B is reduced because of system changes behind B, the apparent fault impedance seen by A may be at C", which is within the OSB characteristic but outside the trip circle. If tripping at C and B is delayed for several cycles, out-of-step blocking may be set up at A, and the fault will eventually be cleared in 3rd zone time. To avoid such incorrect blocking, the relay characteristic shown in Fig. 13C is used, and out-of-step blocking is restricted to the shaded area.

Application of Out-of-Step Tripping Relays

The principal application for the out-of-step tripping relay (Fig. 10) is to obtain tripping at desired locations during a loss of synchronism condition. In many instances, system separation at the desired locations can be obtained with this relay even though the electrical center of the system may change with changing system conditions. For example, consider the system shown in fig. 14A. For the system shown, the desirable point of separation during a loss of synchronism between systems is at bus B leaving a load-generation balance. However, depending upon the system impedances (Z_1 and Z_2), the swing locus may go through section ClD or through section BC. With this variation in swing locus, it would not be permissible to allow the line relays to trip during an out-of-step condition since in one case (swing through ClD) the system to the left would have an excess of load as compared to generation. In this instance, an out-of-step relay at any station, preferably C, could detect the swing and trip the necessary breakers at B via a transfer trip signal. The R-X diagram for this situation is shown in Fig. 14B. It should be noted the out-of-step blocking relays would be used on line sections BC and ClD to prevent tripping by the line relays.

If the loading and generation on the system should change so that the desired point of separation is at one of the other buses, the system operator could transfer the tripping to that bus by means of supervisory control. In the general case, the point of separation which gives a load-generation balance will vary from time to time and therefore, the system operator will have to transfer the tripping to other locations.

Setting of the out-of-step tripping relay is also dependent on the rate of slip between systems. The ohmic setting of the relay (impedances MX and MX' in Fig. 10) should be such that with maximum slip between systems, the swing locus will remain in area between XX' for at least .005 seconds after the relay unit B picks up. The .005 seconds is the operating time of the auxiliary relays which evaluate the sequence of events and ascertain that a loss of synchronism has occurred. In most cases, this criterion does not impose any severe restriction in obtaining a relay setting since relay pickup time plus the .005 seconds auxiliary time represents a slip which is far greater than encountered on most systems. As a general rule, it is also desirable that relay settings be such that load impedance will not fall inside either the A or B characteristic of Fig. 10. This would mean that the characteristics should not fall outside the point where angular separation between systems is less than 90 degrees. Again, this will not impose any restrictions in most applications.

Application of Static Out-of-Step Relaying

The static out-of-step relays discussed earlier and shown in Fig. 11, can provide an out-of-step blocking function, an out-of-step tripping function or both. To obtain al'I of these modes of operations, the only criterion is that the tripping relays (MT or LT) must be set so that tripping will occur only when the angular separation between systems is 120 degrees or greater. The blocking units MOB and LOB would be set in the same manner as described earlier. That is, with maximum slip between systems, it must take several cycles (time "A" in Fig. 11 C) to traverse the distance between the blocking and tripping units. Again, time "A" is adjustable over a range of 2 to 4 cycles. The only restriction on the MOB or LOB settings is that they should not be so large that they will be picked up by load impedance. With the above setting, the static equipment can be adjusted to provide any of the blocking functions and/or the tripping functions provided by the CEX. Moreover, like the CEX, it can detect swings coming from either directions.

Both relay characteristics (circular or lens characteristics) will be applicable on most lines. For example, in the systems shown in Fig. 4 and Fig. 14, either characteristic would be applicable on the line sections traversed by the swing locus. In these cases, there would be no difficulty in obtaining relay settings which fall in the area where the angular separation between systems is greater than 120 degrees.

On the line of Fig. 4, the relay could be used to trip the local breaker, or if separation elsewhere is desired, the fault. The out-of-step tripping output (from AND4) can be connected with links to either trip the local breaker and block reclosing or to permit local blocking and initiate tripping of a remote breaker via a transfer trip channel.

APPLICATION OF OUT-OF-STEP RELAYING

The philosophy behind the use of out-of-step relaying is simple and straightforward. When two areas of a power system or two interconnected systems lose synchronism, the synchronous areas should be separated in order to avoid equipment damage or a system-wide shutdown. Ideally, the systems should be separated at such points as to maintain a balance between load and generation in each of the separated areas. To accomplish this, out-of-step tripping must be used at the desired points of separation and out-of-step blocking used elsewhere to prevent separating the system in an indiscriminate manner. Where a load-generation balance can not be achieved in a separated area and there is excess load as compared to generation, some means of shedding non-essential load will have to be used in order to avoid a complete shutdown of the area.

While this philosophy may be simple and perhaps obvious, it is often difficult to implement an out-of-step relaying program. This is primarily due to the difficulty in obtaining the necessary system information to set the relays. To apply out-of-step relaying on any system, the following information is required.

1. The locations of the swing loci during various system conditions.
2. The maximum rate of slip between systems or system areas.

On some systems, it is possible to obtain the first piece of information by using the approximate procedures outlined earlier in this paper. That is, at various locations in the system, break the system down into a two machine euqivalent. Methods for determining a two machine equivalent are illustrated in references 6 and 7. When an equivalent system is established, locate the swing loci using the approaches illustrated in either Fig. 2 or Fig. 3. In most cases, the swing loci for various generating conditions and system changes can be obtained with this procedure.

On other systems, especially network type systems, it is not possible to use this simplified procedure. On these systems, it is necessary to make a number of transient stability studies covering all possible combinations of operating conditions. With present-day transient stability computer programs, it is a simple matter to obtain an impedance locus at any or all line terminals if necessary during a transient swing.

The second piece of information, the rate of slip, can only be obtained from transient stability studies. As was mentioned earlier, the slip can be estimated from the plots of angular change versus time. Only the maximum slip is of importance and need be determined.

Knowing the swing loci and the maximum slip, it will be possible to obtain reasonable settings for the out-of-step relaying equipments.

Application of Out-of-Step Blocking Relays

It was brought out in the preceding section that the standard out-of-step blocking (OSB) relay characteristic, type CEB12B, is an offset mho circle which is larger than and concentric with the mho tripping relay used for line protection as shown in Fig. 7. The ohmic setting of the OSB relay must be such that with maximum slip between systems, it will take the impedance locus more than 4 cycles on a 60 Hz basis (approximately .064 sec.) to traverse the distance from the OSB characteristic to the mho tripping circle (distance AB in Fig. 7). The 4 cycles is the pick-up time of the auxiliary relay which establishes the blocking function. The only restriction on this ohmic setting is that it should not be so large that the load impedance point can enter the characteristic and establish incorrect blocking of the line tripping relays.

The above criteria will also apply to the characteristics shown in Figs. 8 and 9, and in Fig. 11A and B when the static units are only used in a blocking function. Moreover, the criteria will apply whether the relay is used to block tripping or to block automatic reclosing. When used to block tripping, it is general practice to only block the 1st and 2nd zone tripping relays but not the 3rd zone unit. This is a precaution which provides a means for clearing a phase fault if one should occur when the other units are blocked during a swing.

The application for which the relay is used depends on the system requirements. For the system of Fig. 41 where the systems will be unstable by the time the locus enters the trip relay characteristics, the OSB relay may be used to block automatic reclosing if separation at that point is desirable. If separation elsewhere is desired,, the OSB relay would be used to block tripping.

In the system of Fig. 6, the OSB relay would be used to block tripping since the line relays would trip for swings from which the system could recover. If during a loss of synchronism, system separation is desired at this location, supplemental out-of-step tripping relays type CEX17 would have to be used. It should be noted that it may be difficult to obtain a reasonable setting for an offset mho or impedance out-of-step blocking relay on a system of this type since the required setting may be so large that load impedance may establish incorrect blocking. If static relays are used, the problem may be resolved by using the lens characteristics of Fig. 1113. When electromechanical relays are used (CE131213), the only recourse would be to use blinders, as shown in Fig. 12. One pair of blinders would be used per phase (3 sets required), and they would be set, if possible, to restrict the tripping area so that tripping can only occur for system angles of separation greater than 120 degrees. The OSB relay would then be set with respect to the blinders so that it would take at least 4 cycles for a swing to traverse the distance from the OSB relay could block tripping and transfer trip another line section.

In the system of Fig. 14, out-of-step relaying would only be required on lines BC and CD if the swing loci always went through these line sections. However, it is advisable to include such equipment at all terminals just in case future system changes shift the swing loci to other line sections. If the loci only traverse lines BC and CD, the relays on section CD would be set to block tripping at their own terminals and to transfer trip terminal B when they see an out-of-step condition. The relays at terminal B would be set to trip the local breakers, while the relays at C on line BC, would block tripping, thus keeping the tapped load connected to the system to the right. The blocking and tripping functions could be controlled in any number of ways to meet changing system conditions.

If the line impedance is large as compared to the system impedances, it is likely that only the lens characteristic will be applicable. For example, Fig. 15 shows a system where a circular characteristic could trip for angular differences of less than 120 degrees while the lens characteristic is still applicable. Again, any one of the modes of operation discussed above could be used on this line section.

In general, the lens characteristic will be applicable on a larger variety of lines and systems than the circular characteristic. However, with either relay characteristic, this out-of-step relaying scheme provides greater flexibility with less relay units than in an equivalent electromechanical scheme.

Out-of-Step Tripping of Generators

As a rule, it is not recommended practice to trip generation during an out-of-step condition. It is felt that it is more desirable to split the transmission system where ever necessary, and keep all generation connected to the system or portions thereof. With this approach, this generation will be ready and available to resynchronize the systems and to pick up load. Of course, there will be exceptions to this rule but the consequences of such tripping should be thouroughly evaluated.

Circuit Breaker Duty

It should be noted that when tripping for an out-ofstep condition, the duty on the cirucit breaker should be considered. A suggested test for circuit breakers on out-of-phase switching is to test at twice maximum line to ground voltage with 25 percent transient overshoot at current values up through 25 percent of breaker interrupting rating. This may not be the maximum condition on specific systems but it is considered a practical maximum. To avoid exceeding such breaker capability, tripping should be initiated at a favorable angle between systems (less than 180 degrees separation). There is no problem in achieving a favorable tripping angle with the CEX17 out-of-step tripping relay or with the static out-of-step relaying scheme. However, this factor requires consideration when line relays are permitted to trip during an out-of-step condition since tripping could occur at the point of maximum angular separation (180 degrees). One scheme for tripping at a favorable angle with electromechanical line and out-of-blocking relays is presented in reference 8.

CONCLUDING COMMENTS

This paper has reviewed briefly the factors involved in the application of out-of-step relaying. While the theory and application principles discussed are not new and have been used by the industry for a number of years, there is a need for a reappraisal of the out-of-step relaying practices followed on many power systems. Because of economy in system design and operation, many systems today have smaller margins than ever before between normal operating conditions and transient stability limits. This may be particularly true on the EHV systems being planned and built today.

It was noted that the implementation of an out-of-step relaying program may not be a simple matter. On some sytems it may be impossible to always obtain separa. tion points which will provide a load-generation balance in each separated area under all conditions. In fact, it may be impossible to visualize all combinations of events which may cause an out-of-step condition. In these instances, the only alternative may be to allow the line relays to separate the systems indiscriminately and rely on an load shedding program to prevent a complete shutdown of system areas. In any event, out-of-step relaying and load shedding should receive equal consideration in any effort to minimize the effects of severe system disturbances.

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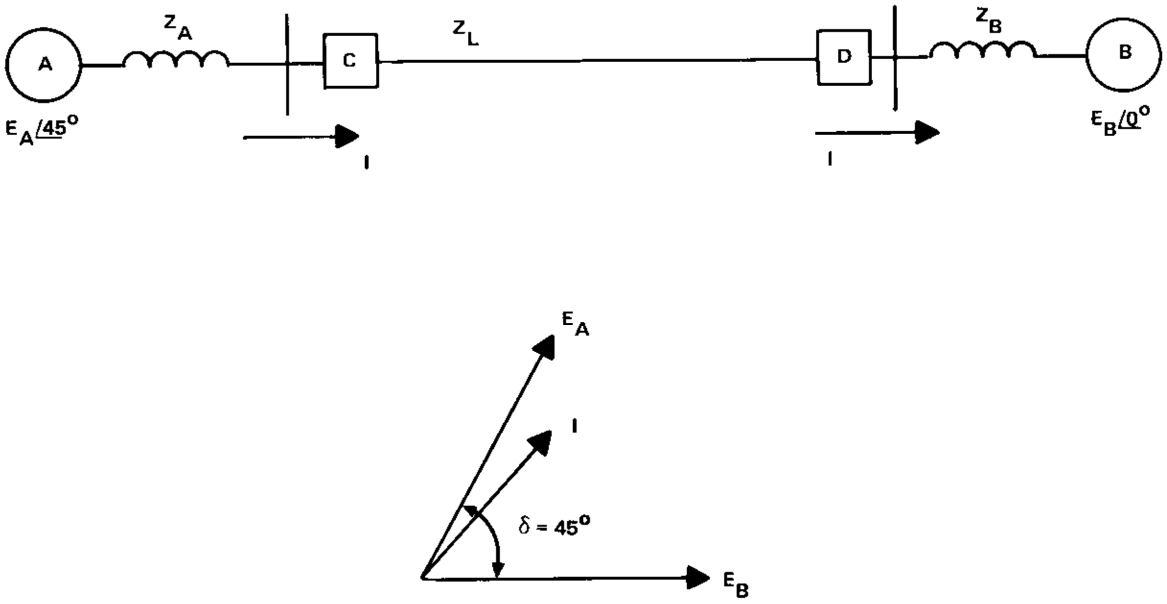
7. "Method for Investigating the Effect of Protective Relay Settings on the System Swing Capability," by J. Davey, F.J. Brown and J.J. Sacks, IEEE Paper 31PP66340, presented at the IEEE Summer Power Meeting, New Orleans, La., July 1966.
8. "Scheme Blocks Out-of-Step Tripping," by R.E. Dietrich, Electrical World, January 3, 1966.



Initial Conditions:
Load Transfer from A to B

Fig. 1. Equivalent system used to determine loss of synchronism characteristic

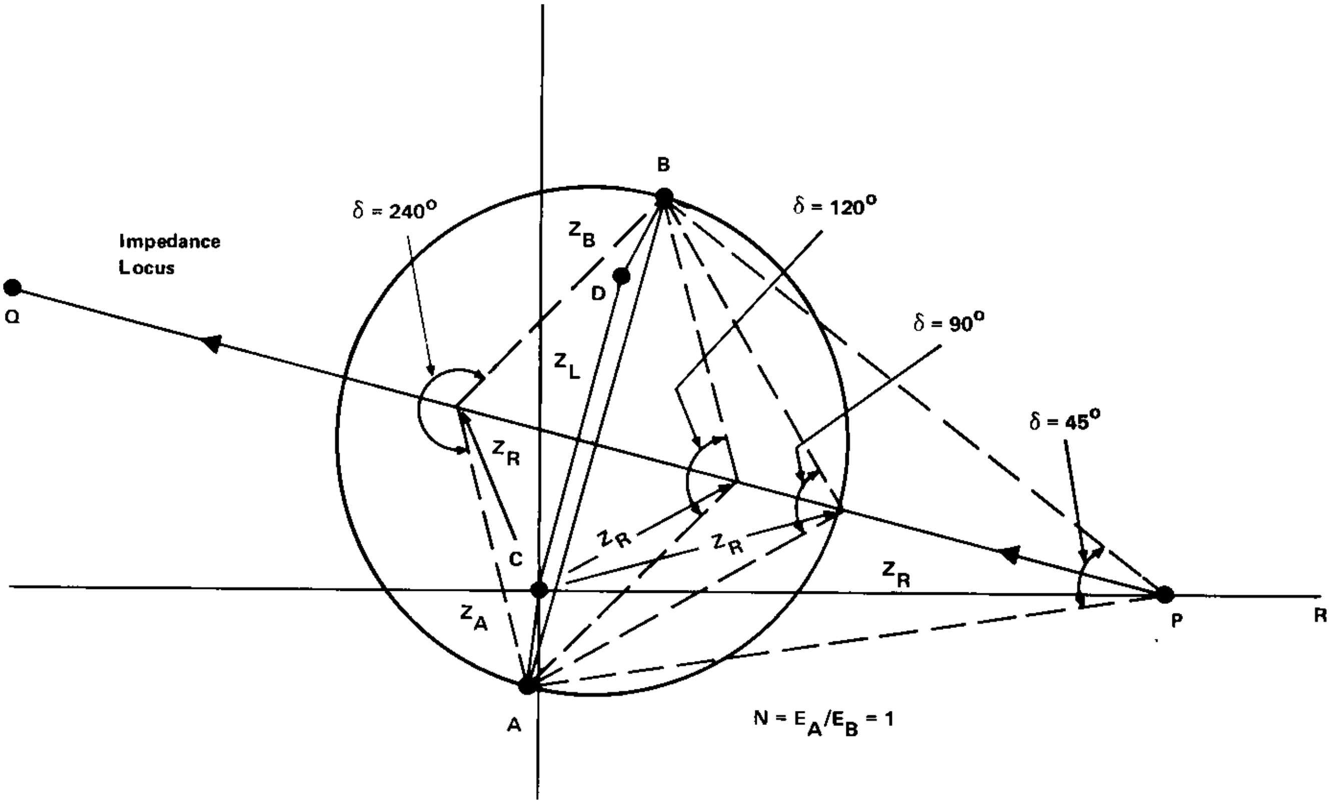


Fig. 2. Loss of synchronism characteristic for the case N = 1

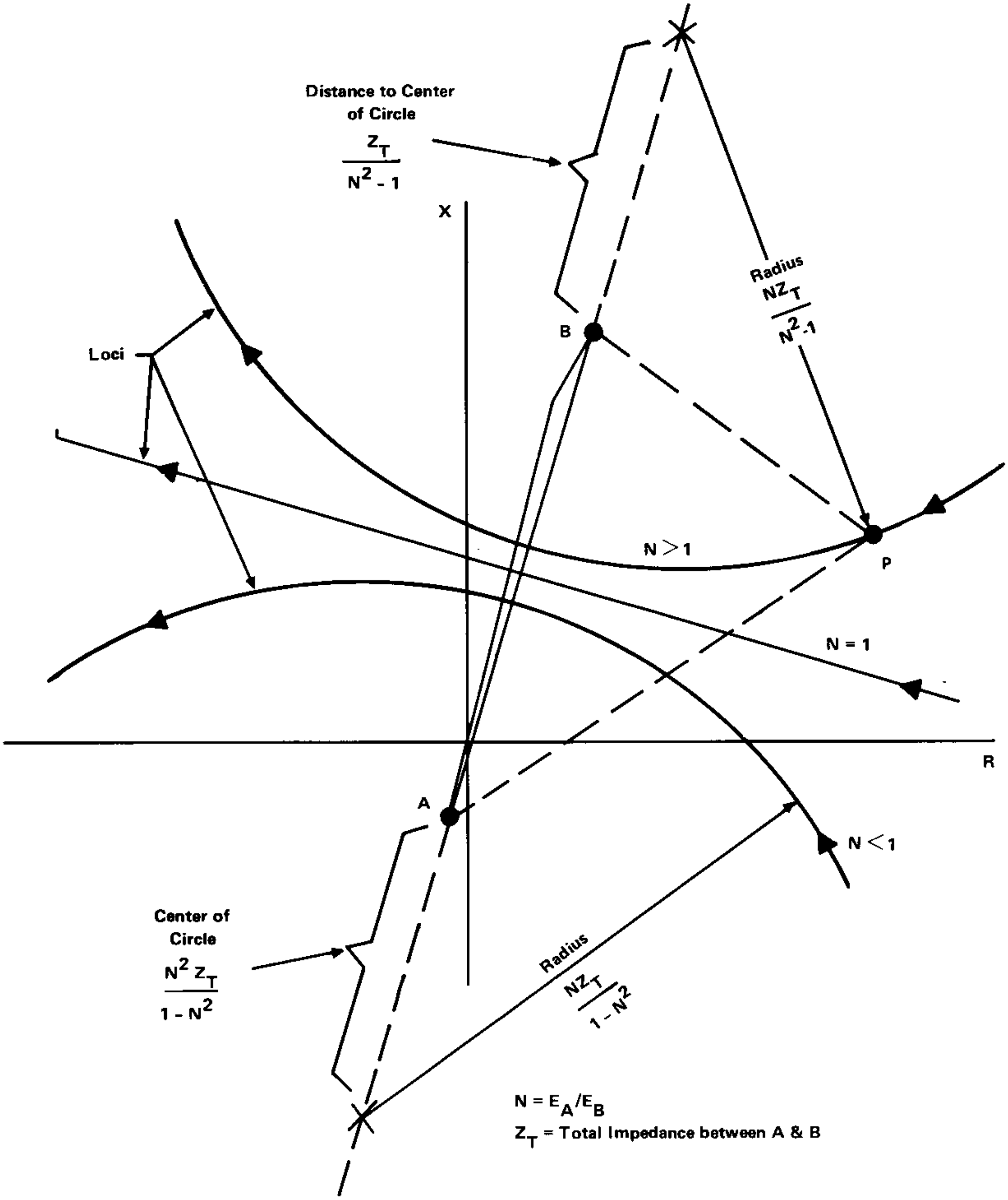


Fig. 3. Loss of synchronism characteristic for cases $N = 1$, $N > 1$, $N < 1$

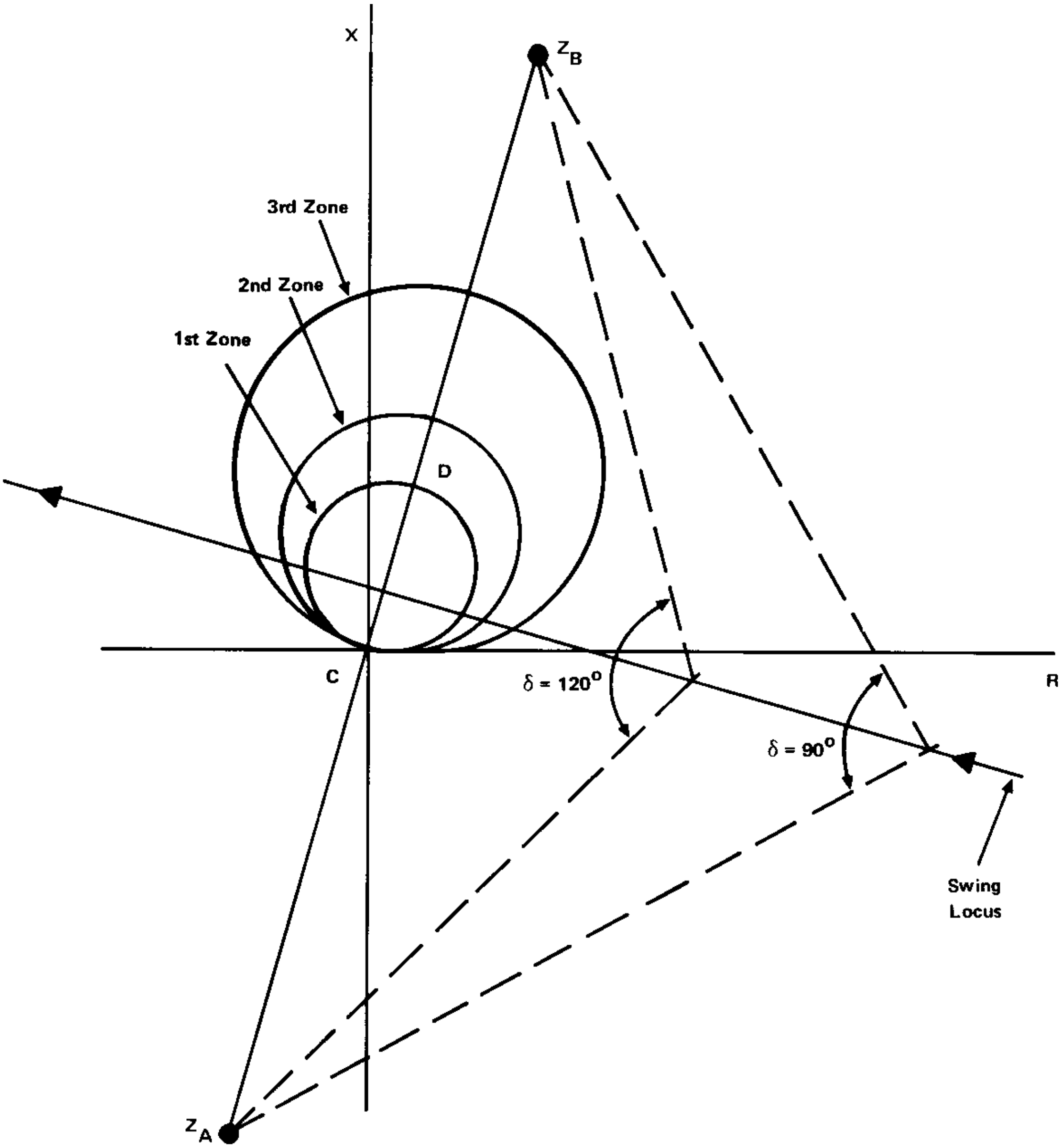


Fig. 4. Effect of loss of synchronism on distance relays – line impedance is small compared to system impedances

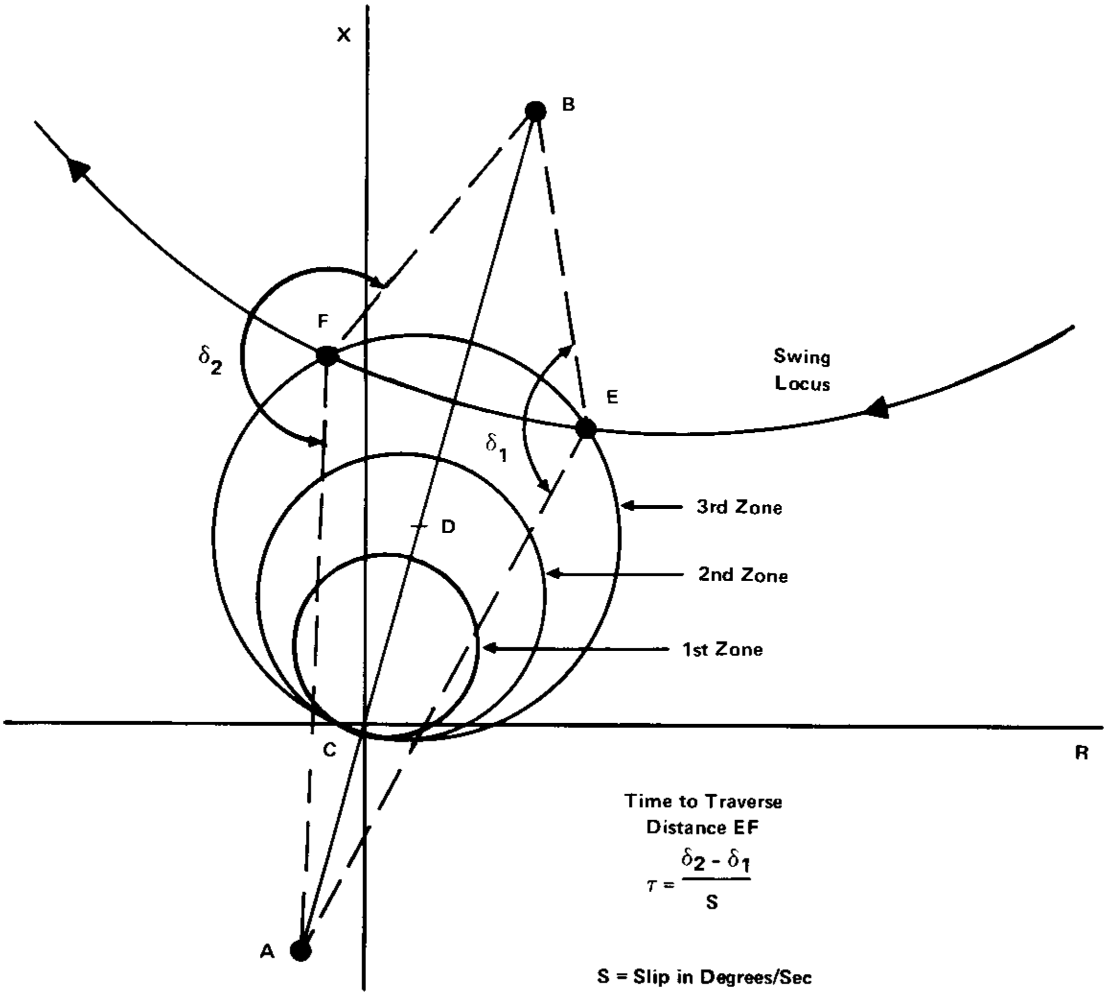


Fig. 5. Method for determining relay operating tendency during loss of synchronism

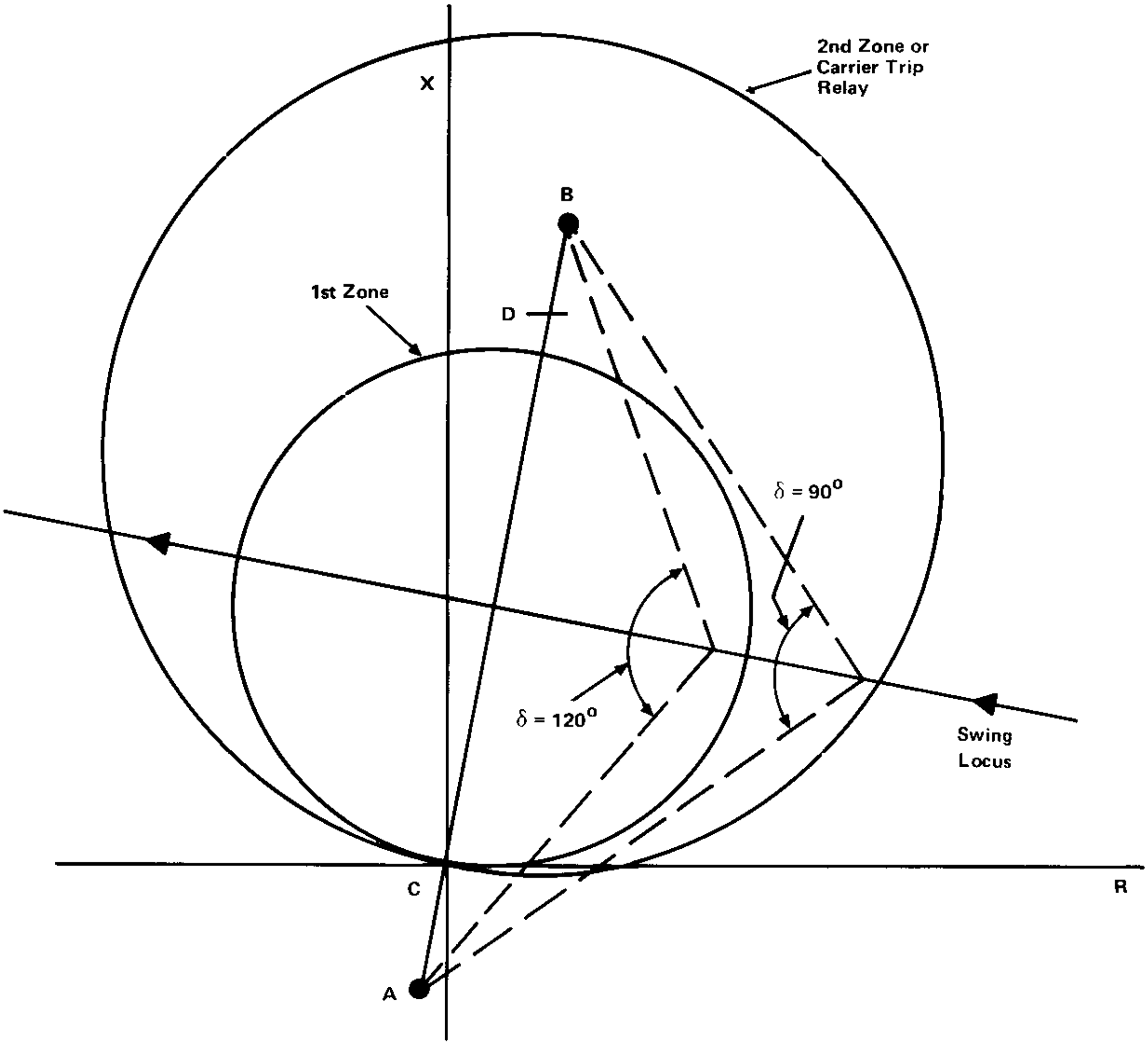


Fig. 6. Effect of loss of synchronism on distance relays — line impedance large compared to system impedance

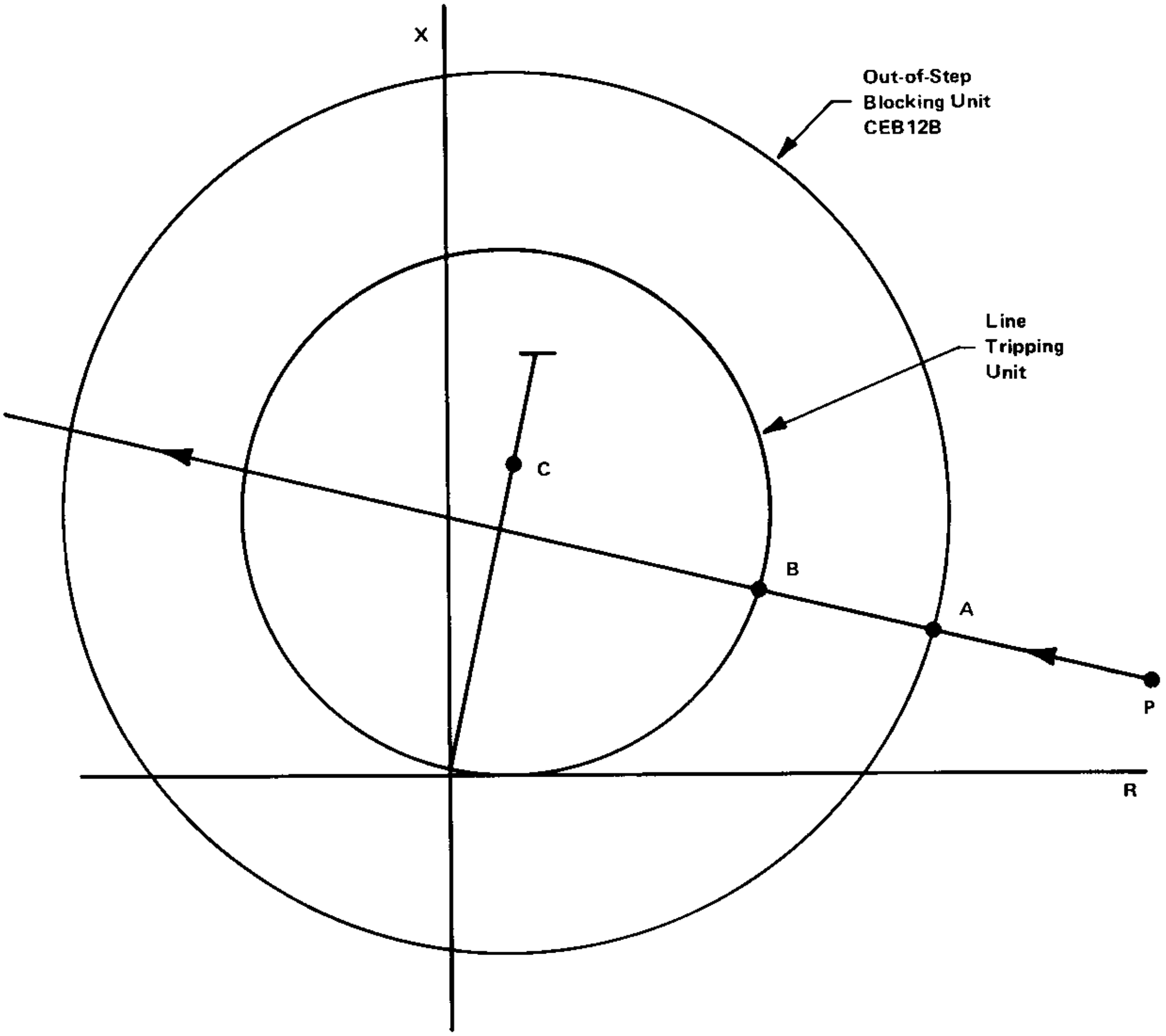


Fig. 7. Out-of-step blocking with an off-set MHO unit

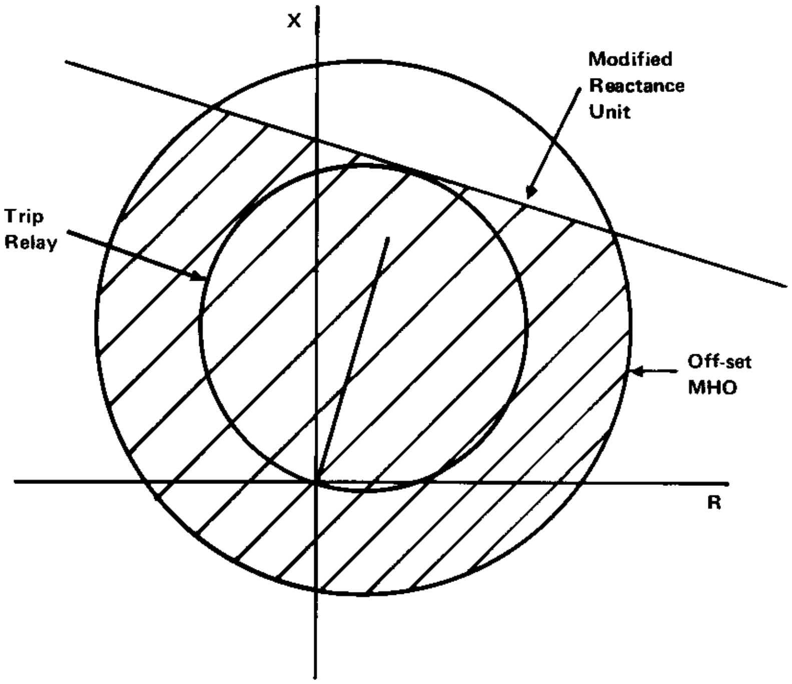


Fig. 8. Modified OSB relay – CEB 14 – for multi-terminal lines

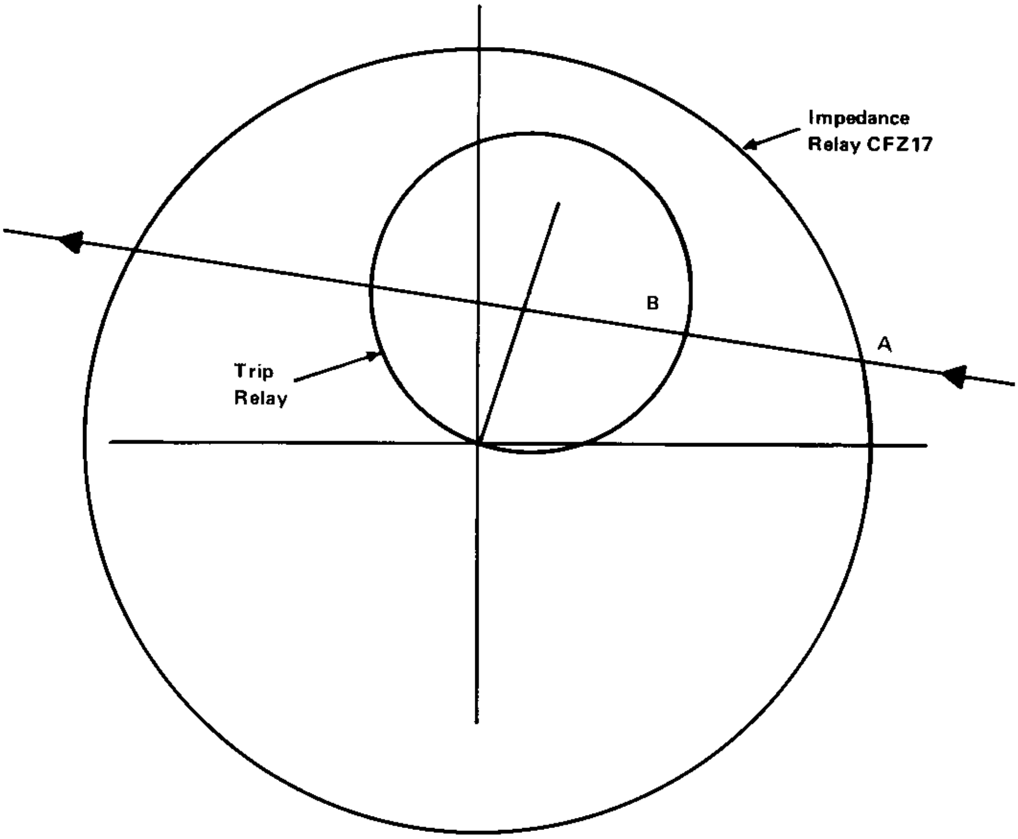


Fig. 9. Out-of-step blocking with impedance carrier start relay

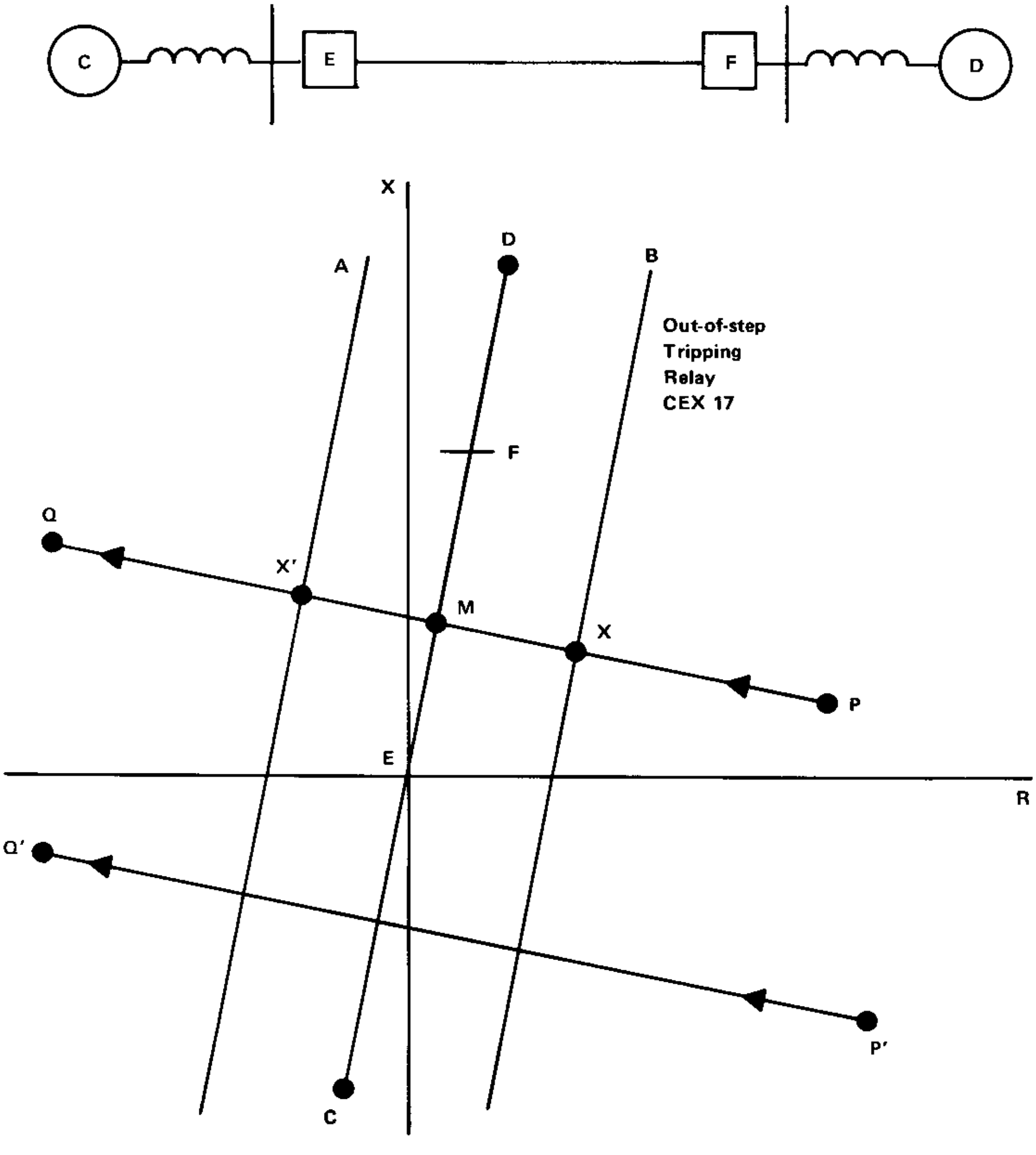


Fig. 10. Characteristic of out-of-step tripping relay

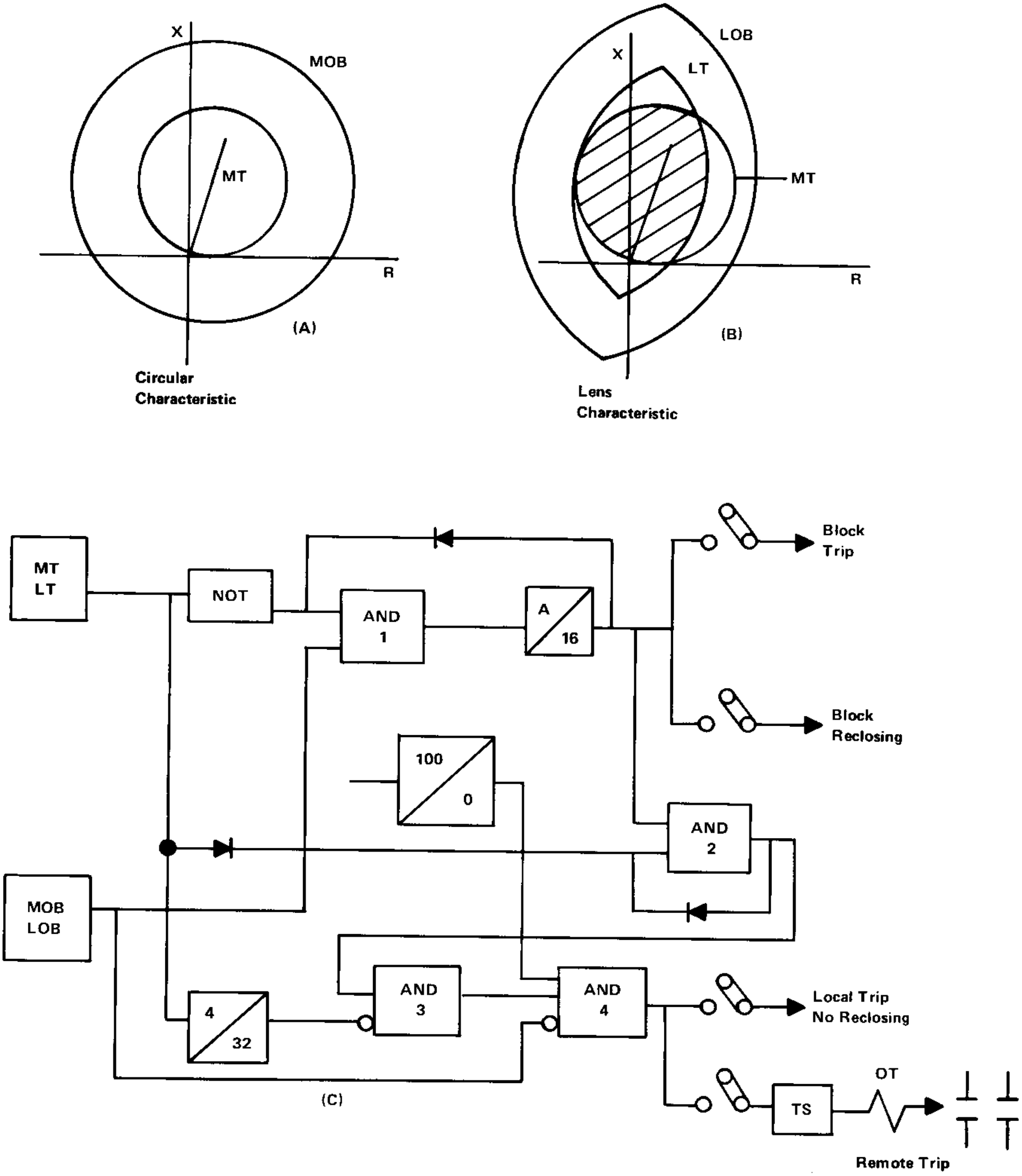


Fig. 11. Static out-of-step relay

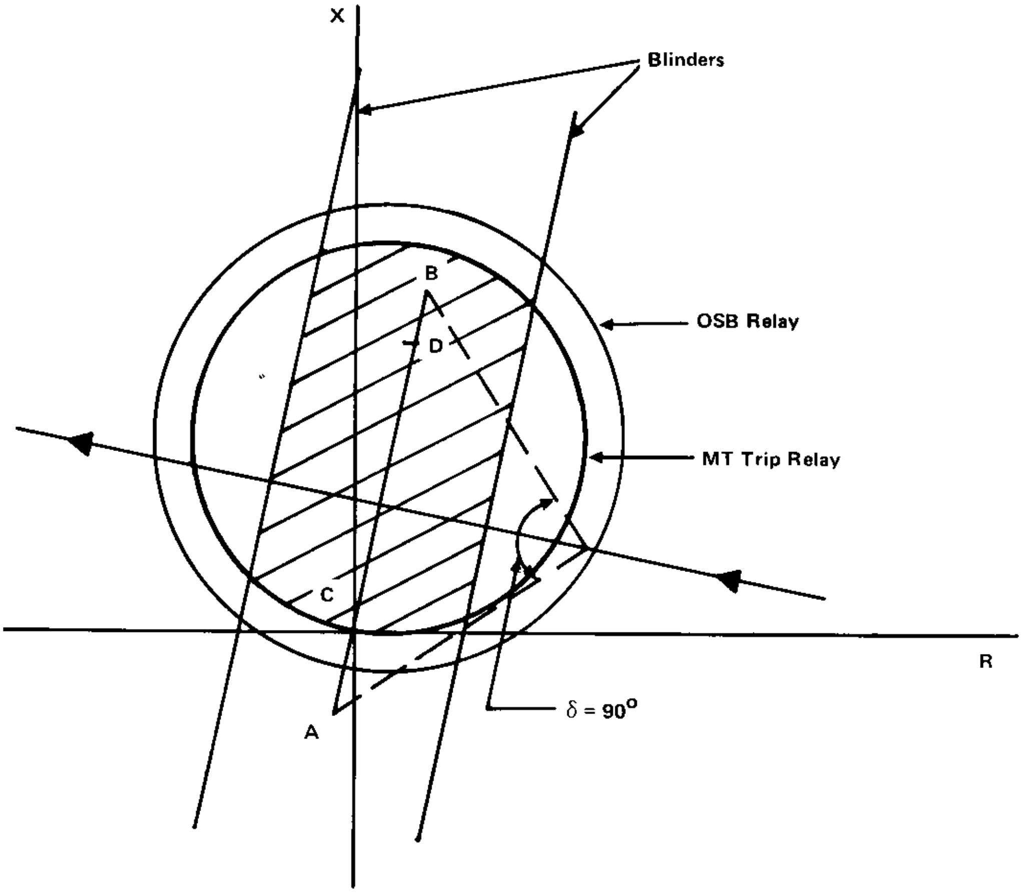


Fig. 12. Use of blinders to restrict tripping area

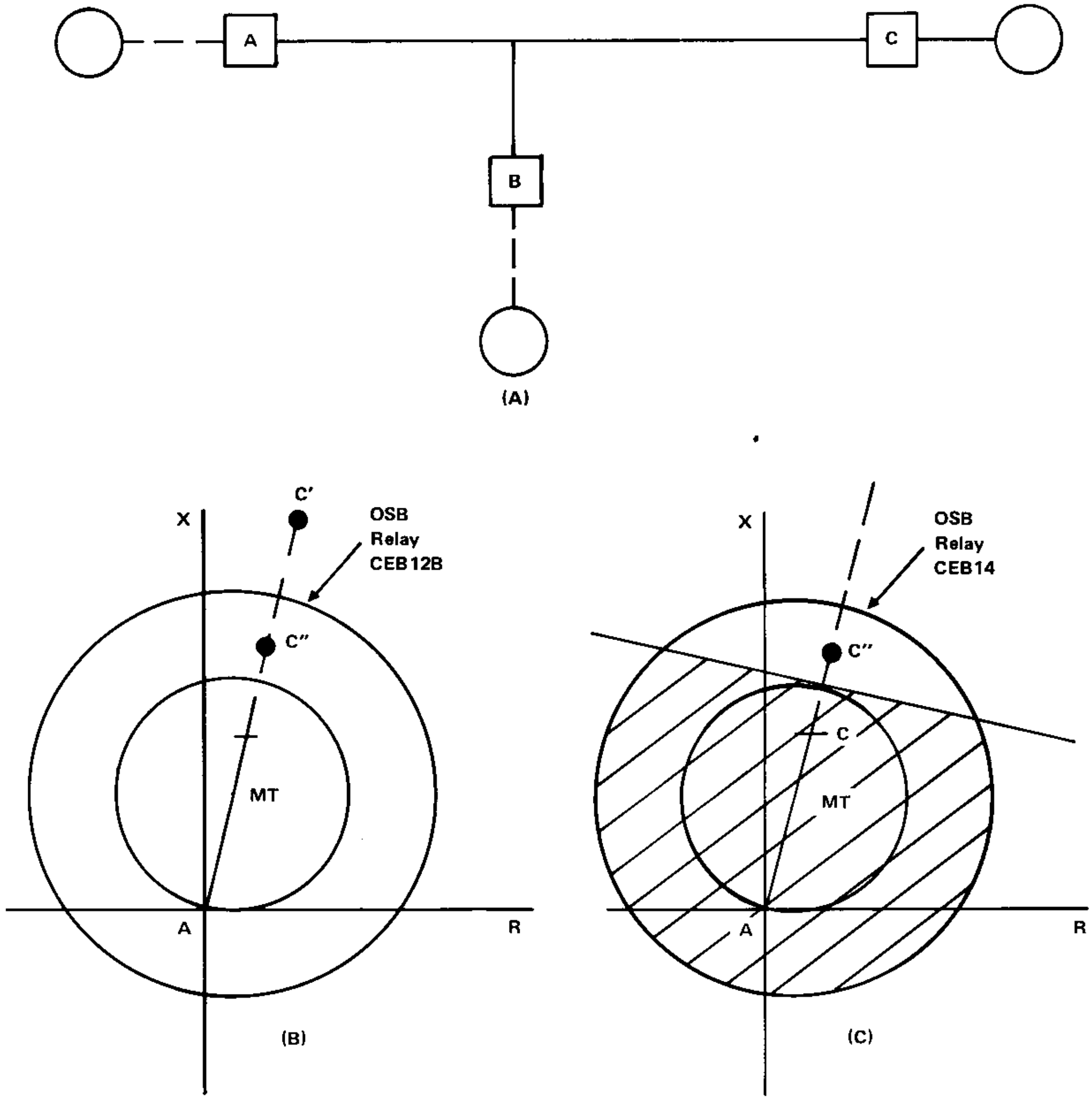


Fig. 13. Application of OSB on a three terminal line

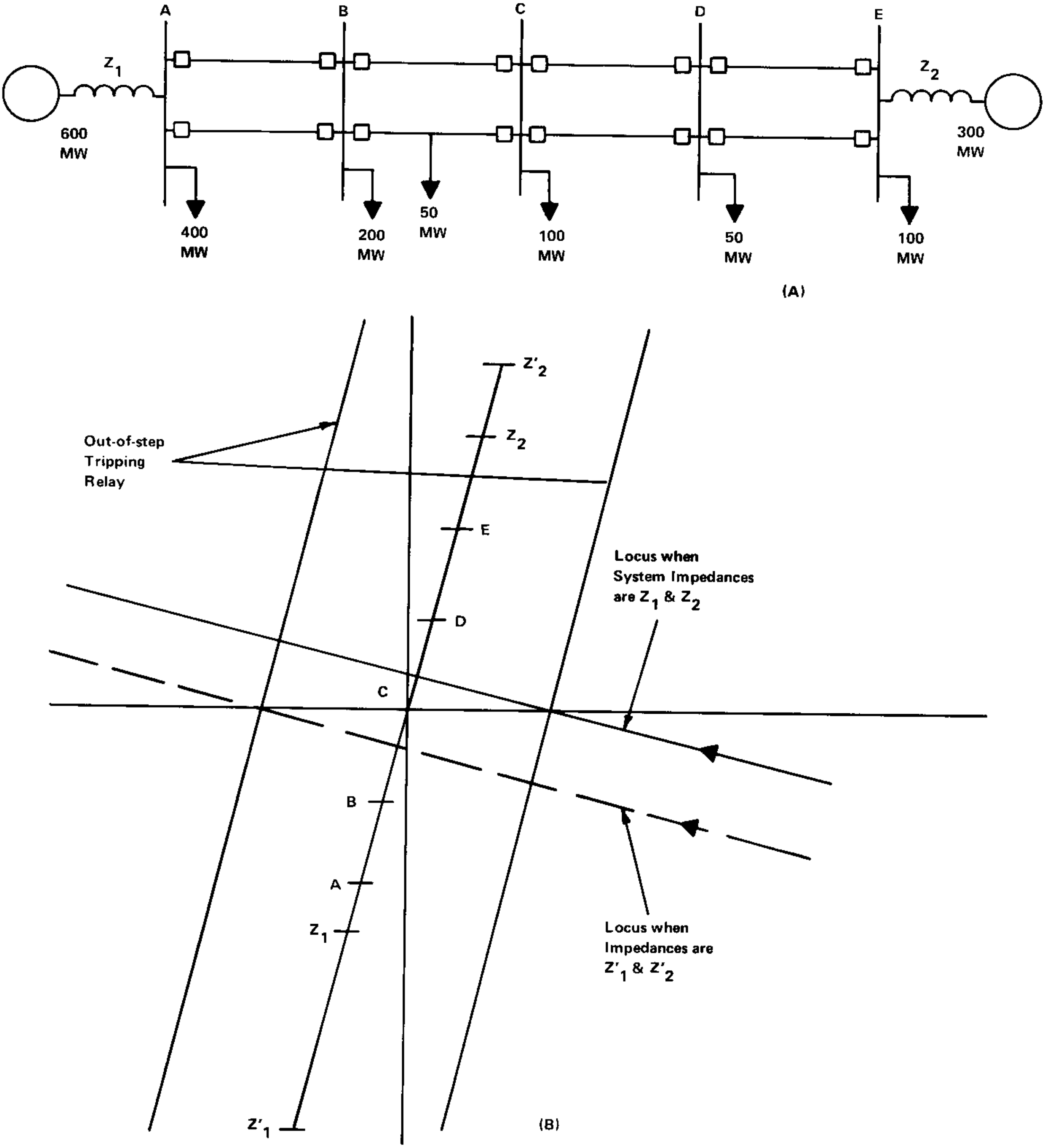


Fig. 14. Application of out-of-step tripping

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