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Series Compensated Line Protection: Evaluation & Solutions

Series Compensated Line Protection — A Practical Evaluation

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The application of series capacitors in HV and EHV transmission systems introduces problems that require understanding before high quality line protection can be achieved. This paper discusses some of these problems with the view of making them easier to visualize and evaluate so that a judicious choice can be made in the selection of a protective relaying scheme to be used on or near series compensated lines. It is not the intent of this paper to present solutions to these problems, but rather to focus on them in a general way by:

a. An examination of their effect on the performance of simple distance and directional type functions.

b. A discussion of their effect on the overall protection used on series compensated lines.

First, however, a brief review will be presented on the application and protection of series capacitors.

SERIES CAPACITORS

Series capacitors are applied to negate a percentage of and hence reduce the overall inductive reactance of a transmission line. The benefits of applying series capacitors on a transmission line include improved stability margins, better load division on parallel paths, ability to adjust line load levels, reduced transmission losses, and reduced voltage drop on the system during severe disturbances.

The application of series capacitors is normally economical for line lengths greater than 200 miles. However, they can and have been applied to lines of shorter length where the line is part of a longer transmission "line" (system). Typically, series capacitors are applied to compensate for 25 to 75 percent of the inductive reactance of the transmission line.

The series capacitors are exposed to a wide range of currents as depicted in Figure 1, which can result in large voltages across the capacitors. In general, it is uneconomical to design the capacitors so that they can withstand these overvoltages, thus additional equipment is usually applied to protect the capacitor. Obviously, the characteristics of this equipment are of concern to the protection engineer.

Effects of Series Capacitor

A. Power Frequency

The reduction of the series inductance of the transmission line by the addition of the series capacitor provides for increased line loading levels as well as increased stability margins. This is apparent by reviewing the basic power transfer equation for the simplified system shown in Figure 2.

The power transfer equation is:

$$P \approx \frac{E1*E2*\mathrm{Sin}(\alpha 12)}{XL\text{-}XC}$$

where P is the power transfer, α12 is the angle between the E1 and E2 voltages, and all other terms are as defined in Figure 2. XC reduces the total transfer impedance thus allowing increased power flow for the same system angle, or a reduction in the system angular separation required for the same power transfer level, thus increasing stability margins. This equation neglects the effects of system resistance, which, when considered, will have an effect in determining the optimum level of compensation.

The other power frequency effect is to increase the fault current levels significantly above those available in the absence of the series capacitor. The capacitor protective equipment will bypass the capacitor for these high levels of fault current.

B. Subharmonics

The series combination of the capacitor and the inductance of the system sets up a series resonant circuit, the natural frequency of which (neglecting resistance) can be calculated by

$$fe = \frac{1}{2\pi\sqrt{LC}} = f\sqrt{\frac{XC}{XL}}$$

where, f is the power system frequency and XL is the total system reactance. Since XC/XL is typically in the range of 0.25 to 0.75, fe will be a subharmonic of the power frequency.

Any system disturbance, including faults, insertion of the capacitor, switching of any series element, etc., will result in the excitation of the system at the subharmonic frequency which in turn can give rise to transient currents. These transients are typically damped out after a few cycles, but may last significantly longer.

In some cases, the subharmonic transient currents may interact with the generators on the system. The presence of the transients in the generator(s) appears as a negative slip frequency on the rotor which is then reflected into the system as a net negative impedance. If this negative impedance becomes larger than the net positive impedance of the system, then the transient currents may grow to intolerable levels unless corrective actions are taken. As for the series capacitor, it will be protected once the current levels increase beyond the protective level of the bypass equipment.

C. Subsynchronous Resonance

The presence of the transients may also excite one or more of the natural torsional frequencies of the mechanical shaft system of the generator(s). This complex phenomena is known as subsynchronous resonance (SSR). Depending upon the degree of damping and resonance, the torsional oscillations may be severe enough to cause damage to the shaft. Large steam turbine generators are most susceptible to SSR due to their having 2 to 5 torsional modes that are typically in the frequency range of 5 to 55 Hz.

Usually, the potential for subharmonic transients and SSR are investigated and corrective action is taken to mitigate their effects.

Protective Equipment

As mentioned earlier, protective equipment is applied to the series capacitor to protect it from the excessive voltages which can occur during faults. This equipment takes one of two basic forms: a parallel power gap or a metal-oxide varistor (MOV).

A. Parallel Power Gap

Up until the late 1970s, the power gap was the primary means of providing overvoltage protection of the series capacitor. A simplified schematic of this system is shown in Figure 3. The gap provides protection for the capacitor by sparking over when the voltage across the capacitor exceeds a specific level. This level is known as the protective level. Usual values of protective level are 2.5 to 4.0 times normal operating voltage. A reactor is placed in series with the gap to limit the capacitor discharge current through the gap. Once current flow is initiated in the gap, a parallel bypass switch is closed to extinguish the arc in the gap. The bypass switch remains closed for a period sufficient to allow the gap to recover and then is opened automatically to reinsert the capacitor.

If the capacitor has been applied for transient stability improvement, then high speed reinsertion of the capacitor as well as high speed fault clearing is desirable. One means of providing high speed insertion is the use of a vacuum gap in place of the air gap. The vacuum gap has excellent recovery voltage withstand which allows for high speed opening of the bypass switch. Another system has achieved high speed reinsertion by extinguishing the arc by air blast rather than by closure of a parallel bypass switch. This system initiates air flow immediately upon detection of gap current. A drawback of this system is the potential for multiple sparkovers of the gap for the same event which places added stress on the capacitor.

The selection of the protective level is based on the ability of the gap to withstand the various system transients such as depicted in Figure 1. Of particular concern for a gap is its ability to withstand the reinsertion transients. As previously discussed, the reinsertion of the capacitor gives rise to subharmonic transients. These transients are superimposed on the normal power frequency system swings which follow the clearing of the fault. The gap must be able to withstand the combined overvoltage which results. This results in variability in the gap sparkover level when evaluated on the basis of 60 Hz current flow only. The peak of this combined transient current may occur approximately 1/2 second to as long as several seconds after reinsertion.

Due to the limitations in the ability to build large voltage gaps, banks which are protected by gaps are made up of multiple series/parallel segments. The sequential insertion of these segments can result in increased reinsertion transients and non-simultaneous gap flashing.

B. Metal Oxide Varistor

The 1980s have marked the widespread use of metal oxide varistors for transient overvoltage protection for series capacitors. Figure 4 is a simplified schematic for this system. The MOV is connected directly across the capacitor with no intervening reactor or gap. The exceptional nonlinearity of the

MOV results in no conduction through the MOV during normal system conditions. On the occurrence of a fault the current through the capacitor increases, giving rise to an increase in the capacitor voltage. The MOV begins to conduct when this voltage approaches the protective level and acts to clamp the voltage to the protective level. This clamping action occurs each half cycle with conduction alternating between the capacitor and the MOV as shown in Figure 5. On removal of the fault, the MOV will cease to conduct except for the occasional peak voltage of the post fault transient. The energy duty of this transient is typically small in comparison with the energy requirements associated with the fault currents.

The MOV has stable and defined voltage and energy characteristics upon which the MOV ratings are established for each application. Since the MOV has eliminated concerns for the recovery voltage withstand of the gap, protective levels have been reduced to a range of 2.0 to 2.5 times normal voltage. The protective level is usually specified to be above the system swings (see Figure 6) although it may conduct on some of the initial post fault transients as mentioned above. The specification of a MOV requires the definition of the system conditions for which the energy rating of the MOV will be established. The MOV is usually required to have sufficient energy capability to ride through worst case external fault scenarios thus allowing the capacitor to remain in service at the time it is most needed. A parallel gap is provided to protect the MOV when its energy rating has been reached. This gap is triggered by protection circuits which monitor the energy duty of the MOV. When the energy rating is reached the gap is fired.

For internal line faults, there are a number of approaches available for the specification of the energy rating of the varistor. Obviously, the energy available is a function of the location of the capacitor bank and this will affect the type of system selected. Some systems have been applied which allow bypassing of the varistor for any internal fault. The varistor protection circuits monitor the MOV and trigger the gap upon detection of a high level of current flow or high rate of rise of energy. Depending on the detection and triggering circuits, fault severity and fault initiation angle, bypassing of the MOV may be effected in as little as 2 ms after fault initiation. However, bypassing may not occur if the fault is not severe enough to cause pickup of these circuits. Delayed bypassing may occur due to pickup of the energy monitor circuits.

Some utilities have specified their MOV protection based on the ability to withstand a worst case internal three phase fault lasting for 5 cycles. This conservative definition of the energy rating of the MOV means that it is highly unlikely that the MOV will ever be bypassed for an internal line fault. Others have eliminated the gap completely and rely on the bypass switch for protection of the MOV on internal faults. For these systems, a switch which can close in three cycles is used.

A SIMPLE DISTANCE FUNCTION

As an aid to understanding the response of a distance relay on a series compensated line, a simple distance function using a phase angle comparator will be examined. A block diagram of this function is shown in Figure 7a. The operating signal (VOP) is IZ-V, where IZ is the voltage output of a replica impedance circuit and V is the voltage at the relay. For a function that has infinite memory, the polarizing voltage (VPOL) will be equal to the prefault voltage. For a function with finite memory, the voltage will initially be equal to the prefault voltage and will then be equal to the relay voltage when the memory dies out.

The phase angle comparator shown in Figure 7a will produce an output if the angle between VOP and VPOL is less than the characteristic timer angle setting. It does this by measuring the coincidence between VOP and VPOL; i.e., the period of time when both signals are of the same instantaneous polarity. When the coincidence time exceeds the characteristic timer pickup setting, the function produces an output. For the circular mho characteristic of Figure 7b, the timer is set to 90°. Typical signal waveforms and concurrent coincidence blocks are shown in Figure 7c.

A SIMPLE DIRECTIONAL FUNCTION

The phase angle comparator circuit can also be used to develop measuring functions other than a mho distance function. For example, if the operating signal IZ-V is replaced by IZ only, a simple directional function is formed. This function will produce an output whenever IZ (VOP) and VPOL are coincident for more than the characteristic angle setting. The associated phasor diagrams are shown in Figure 8. This simple directional function can be improved by the addition of a "compensating" input to the polarizing signal. In a compensated directional function using a phase angle comparator, the operating signal remains IZ but the polarizing signal is changed to V + K(IZ), where K(IZ) is proportional to the operating signal.

CLASSICAL PROBLEMS

Probably the most recognizable problems associated with the relay protection applied to lines with series capacitors are those related to the voltage and current reversals that can occur. For purposes of the following discussion, it will be assumed that all impedances are purely inductive or capacitive, and that there is no load flow across the system. Inclusion of these factors would take away from the simplicity of the discussion and, with the exception of load flow, would have minimal affect on the conclusions to be drawn. Some of the effects of the load flow will be discussed in a later section.

A. Voltage Reversals

A voltage reversal will occur for a fault near a series capacitor when the impedance from the potential location to the fault is capacitive rather than the inductive value normally encountered in an uncompensated system. As a result, the voltage applied to a relay at the potential location will be shifted approximately 180 degrees from what can be considered the normal position. Since the simple distance function described earlier is designed to work properly on an inductive system, the voltage reversal will have an effect on the performance of the function.

For example, consider the system shown in Figure 9 and assume that a simple distance function is located at Station A, that it is looking towards Station B, and that it is supplied from a potential source located on the line side of the capacitor as shown. For a three-phase fault on the bus at Station A (F1), the voltage applied to the function will be the drop across the capacitor and consequently will be reversed from the position normally encountered in an inductive system. This is shown in the phasor diagram of Figure 9a which applies for the condition of the relay reach (Z) being greater than the capacitive reactance (XC1). For a polarizing circuit that is equipped with finite memory, two conditions can be noted:

1. The input voltage to the comparer will initially be equal to and in phase with the source voltage E because of the memory. For this condition, the function will not operate while the memory lasts because the operate signal (VOP) and the polarizing signal (VPOL) are 180 degrees out of phase with each other. This period of operation is referred to as the dynamic period of operation.

2. The input voltage of the comparer of the distance function will be equal to the relay voltage V when the memory dies out, and the function will operate because the operating signal (VOP) and the polarizing signal (VPOL) are in phase with each other. This period is referred to as the steady-state period of operation.

Finite memory circuits are used in most practical distance functions, thus for the conditions noted above, the function will operate correctly on a dynamic basis, but will operate incorrectly steady-state.

In most applications, the reach of the functions will be set larger than the capacitive reactance; however, if the reach of the function is reduced below this value, the opposite will occur and the function will operate correctly steady-state but will operate incorrectly on a dynamic basis. Similar operation can occur for a fault at F2 if the relay voltage V (the drop across the capacitors C1 and C2) exceeds the IZ portion of the operate signal. This condition can occur because of the effect of infeed to the fault from any source located at Bus A.

It is likely that capacitor C2 will be bypassed for the fault at F2 because of infeed, but not so likely that capacitor C1 will be bypassed for the fault at F1. The probability exists therefore that the simple distance function will not operate reliably, and this is one of the reasons (others to follow) that it is not recommended for use by itself in the protection of series compensated lines.

A voltage reversal can also occur in the sequence networks if the net impedance as measured from the potential location back to the source is capacitive. Consider the system in Figure 10a. For a fault at F2, the negative sequence and zero sequence voltages at the potential location shown will be reversed if the respective source impedance is less than the reactance of the series capacitor. Figure 10c shows the voltage profile for the negative sequence network assuming that XS is less than XC. A negative sequence directional function placed at that potential location and looking toward station B would not operate correctly for this condition because of the voltage reversal. The directional function can be compensated to overcome the reversal and so made to operate properly for the conditions shown. Note that the voltage on the bus side of the capacitor is not reversed so that a directional function that uses bus side potentials will operate correctly.

For a fault at F1, the potential on the line side of the capacitor will again be reversed so that an uncompensated directional unit located there will not operate correctly. However, a compensated directional function will operate correctly. It can be argued that the capacitors will most likely be bypassed for this fault because the fault current will be very high. This may be true for a bolted fault, but may not be for a fault involving high resistance.

B. Current Reversals

A current reversal is said to occur when the current appears to be entering at one end of the line and leaving at the other, just as would occur during an external fault. This can occur for the F1 fault shown in Figure 10a if the source impedance XS is less than the capacitive reactance XC. This may be an impractical condition for a bolted fault since the large fault current would insure rapid bypassing of the capacitors. However, in the case of faults with large fault resistance, the fault impedance can reduce the fault current below the bypass level.

A simple negative or zero sequence directional function would work correctly at the right end of the line, but would only work correctly at the left end if the potential source was located on the bus side of the series capacitor. A simple negative or zero sequence directional function would not work correctly at the left terminal of the line with line side potential because the voltage would be reversed from normal. A compensated directional function could be made to work correctly at the left terminal, even with the use of line side potential.

Schemes that use current only for operation will be blocked by the fault current reversal depicted in Figure 10a unless they are modified to obtain reliable operation.

A special case of the current reversal problem occurs for a fault at F1 when XS is approximately equal to XC in which case the fault current will approach zero at the right end of the transmission line. Consideration should be given to two points:

1. Does the scheme selected operate if one end of the line does not see any change in voltage or current?

2. If both ends of the line must be tripped in high speed, will the method selected to obtain high speed tripping significantly affect the overall reliability of the system?

If single pole tripping is employed, current phase selection at the terminal remote from the fault is particularly onerous as the fault current, or the change in current, at that terminal approaches zero:

Figure 11 illustrates a case where a fault current reversal can occur even if XS is significantly larger than XC. In this case, a fault current reversal will occur if the voltage drop across XC is greater than the voltage drop across the lower line (including the capacitors).

TRANSIENT PROBLEMS

A. Basic Circuit Considerations

In lines without series capacitors, the primary transient associated with a fault is a decaying dc. On lines with series compensation, however, the primary transient is an ac signal with a frequency that is determined by the series capacitance and the system inductance. It was noted earlier that the frequency of this transient is generally lower than the fundamental frequency because the value of XC is less than the value of XL. In theory, the transient could be higher than the fundamental frequency if XC is greater than XS, but the high currents developed during a fault would cause operation of the series capacitor protection which would preclude the higher frequencies by bypassing the capacitors. Operation of the series capacitor protection will also modify the low frequency transients. To illustrate the problems a simple radial system shown in Figure 12 was studied on a personal computer and on an analog model power system. Figure 13 shows the source voltage for each case with a nominal value of 67 volts rms. The line impedance ZL is 12 ohms at 88°. The capacitor is 6.6 ohms at -90° (55 percent compensation), and is without any protective device. Figure 14 shows the current waveforms for the case of ZS of 18 ohms at 88° for a fault incidence angle (referred to the source voltage) of 0° and 90°, respectively. Relay settings, even on lines with series capacitors are generally based on steady state values of fault currents and voltages. Because of this it is worth noting the disparity between the steady state current peaks and the transient current peaks in Figures 14a and 14b. The dotted horizontal lines indicate where the steady state fault current peaks would normally occur. The ratio of the maximum transient peak to the steady state peak is 1.9. The higher peak currents may affect the performance of the protective relays, especially overcurrent units. They may also cause operation of the series capacitor protection for faults that have a steady state current less than the protective level, thus complicating the analysis of the relay performance. Distance relays typically include a replica impedance circuit which, in addition to creating a replica of the transmission line, also acts as a filter on the current circuits. Figures 15a and 15b show the waveforms of the transactor output, or IZ signal, for 0° and 90° respectively where the replica impedance, Z, is 1 ohm at 88°. The magnitude of 1 ohm was chosen so that the steady state magnitude of the IZ signal is the same as the steady state magnitude of the current signal in Figures 14a and 14b. Note the much lower ratio of the peak signal to the steady-state signal for the IZ as compared to the equivalent ratio of the current. The replica impedance circuit has reduced the disparity between the transient peaks and the steady state peaks but has not totally eliminated the problem.

In Figure 16 an IZ-V signal has been obtained by subtracting the voltage at the relay location from the IZ signal (Z = 2.7 ohms, which is equal to 50% of the compensated line impedance). Operation of the simple distance function shown in Figure 7a can be evaluated by comparing the VOP (IZ-V) signal with the polarizing signal, VPOL, which in this example is equal to the source voltage (assumes an infinite memory circuit). The blocks indicate areas of coincidence. If the coincidence timer is set for 90° (4.2 milliseconds on a 60 Hz system) to provide a circular mho characteristic, it can be seen that four coincidence blocks are wide enough to operate the relay. (Note that in these cases it is assumed that the protection on the series capacitor does not operate). Figure 17 shows the relay still operating with the relay reach reduced to zero, but the number of blocks that would produce an output is reduced to two. This means that the simple distance function which is being evaluated will overreach and false trip for any reach setting.
Figure 18 is for a case similar to Figure 16 except the fault incidence angle is 90° on the voltage wave. For this case, only one coincidence block is long enough to operate the relay.

Whether or not the simple distance relay overreaches for the fault on the remote bus as described in the above cases will largely be determined by the capacitor protection. If the capacitor protection does not operate, the relay will overreach; if the protection operates, the relay may not overreach. Whether or not the capacitor protection operates will be dependent on the protective level. Figure 19a shows the voltage across the capacitor for an incidence angle of 0°. Figure 19b shows the capacitor voltage for an incidence angle of 90°. The peak voltage on the capacitor is substantially lower for the 90° incidence angle than for the 0° incidence angle, and therefore less likely to cause the protection to operate.

Figures 20a and 20b show the series capacitor voltages for the case where the source impedance ZS is equal to 6 ohms. In these cases, the capacitor voltage is so high that operation of the protection is assured. As the source impedance is increased, the capacitor protection is less likely to operate because of the concurrent reduction in fault current and hence in the voltage across the capacitor.

Figure 21 shows the capacitor voltage for a source of 36 ohms. Note that the capacitor voltage is relatively low and therefore the capacitor protection is unlikely to operate. Figure 22 shows the operating signal (VOP), the polarizing signal (VPOL), and the coincidence blocks for the simple distance relay with this same 36 ohm source impedance. If it is accepted that the capacitor protection has not operated, it can be concluded from Figure 22 that the simple distance function will overreach because most of the coincidence blocks are wide enough to cause operation.

As noted previously, the protection on the series capacitors will modify the voltage and current signals and hence the relay performance. In the case of series capacitors protected by trigger gaps, when the capacitor voltage reaches the trigger level, the capacitor is immediately bypassed. In the case of series capacitors protected by MOV's, the MOV's must conduct sufficient current at high capacitor voltages to protect the capacitors. In the case of very high fault currents, trigger gaps are usually fired to bypass the series capacitors to protect the MOV's. Thus, on very high fault currents, the MOV protected series capacitor is similar in operation to the trigger gap protected capacitor except the trigger gaps on the MOV protected capacitor may be faster or slower in firing. However, on external faults, the MOV's will generally have sufficient thermal capacity to handle the lighter fault currents, and the associated trigger gaps will not be fired.

Thus, where the series capacitors use MOV protection, relay performance is much harder to evaluate because the capacitors are either in the circuit, or they are bypassed by trigger gaps, or they are bypassed by a non-linear resistance (the MOV's). In the case of the MOV protected capacitors, there is a transition period starting with conduction of the MOV on a transient basis and ending when the capacitors are bypassed. In general, the greater the current conducted by the MOV, the less likely the distance function is to overreach.

Figure 23 shows VOP for the case of a 24 ohm source impedance. The system is the same as Figure 12 and the relay reach is again set for 50 percent of the compensated impedance of the line (2.7 ohms). The upper blocks show the coincidence between VOP and the polarizing voltage VPOL without protection on the capacitor. The blocks below show the coincidence between VPOL and VOP (not shown) when MOV's are added across the capacitor. The MOV protection level is 0.6 of the peak rated system voltage. For this case, the simple distance relay operates with or without the MOV, but it stays operated for a shorter time when the MOV's are in the circuit.

Figure 24 illustrates essentially the same case using the GE Model Power System (MPS) except with a different fault incidence angle than used in Figure 23. In this case, the VOP signals with and without MOV's are shown. For this incidence angle, the simple relay operated with or without the MOV's but only one block was wide enough to cause operation when the MOV's were added. The initial high frequency transient is due to the shunt capacitance of the line which was not included in the simplified computer model. This again indicates the dependence of the relay performance on the fault incidence angle.

Figure 25 illustrates a typical model power system setup with 18 ohms sources at each end of the two parallel lines. The relay reach is 3 ohms. Figure 27a shows VOP and VPOL for a fault at F1. The relay overreaches for this case. With the parallel line in service, this tendency to overreach will be greater due to the lower current in the line (equivalent to a larger source impedance). Figure 27b shows VOP and VPOL for a fault at F2. Initially, the conduction of the MOV in the parallel line makes the fault look somewhat resistive and the relay does not overreach. However, in about 1.25 cycles, the capacitor in the parallel line is bypassed and the relay subsequently overreaches. Thus, in a typical system, the F1 fault will be more likely to cause overreaching of the direct trip unit at the left end than would the F2 fault.

It was noted earlier that the directional integrity of a distance function could be affected in the presence of series capacitors. Figure 28 shows the coincidence of VOP and VPOL for a distance function with a 2.7 ohm reach for a capacitive fault behind the function as shown in Figure 26. As explained in the section under steady-state problems, the function will operate on a dynamic basis because the reach (2.7 ohms) of the function is less than the reactance of the capacitor (6.6 ohms). With a finite memory circuit, the function will cease operating when the memory dies out. Figure 29 shows the coincidence blocks for the same function, and the same fault, but with the reach increased to 18 ohms. In this case, the function will not operate dynamically because the reach of the function is now greater than the capacitive reactance, but would operate steady-state when the memory dies out. Based on this, it may be possible to use a distance function for direct tripping, but the reach setting would have to be a compromise:

1. Short enough to prevent overreach for a fault in the forward direction (may not be possible because it was shown earlier that a function could be made to operate with zero reach).

2. Long enough to prevent a dynamic loss of directionality for a fault in the reverse direction. For this condition, some means would have to be used to prevent steady-state operation when the memory dies out.

B. Gap Flashing Transients

When the trigger gaps operate to bypass the series capacitor bank, the energy in the capacitor is discharged through a reactor. This produces a high frequency voltage transient across the capacitor bank. If a fault ties one side of the capacitor bank to ground, then this high frequency voltage is impressed on the system on the other side of the bank. If the relay potential location is the opposite side of the bank to the grounded side, then the high frequency voltage will be applied to the relays. If the fault is on the line side of the series capacitor bank, then the high frequency voltage is applied to the shunt capacitance of the adjacent lines, resulting in a high frequency current flowing. These high frequency transients may have very large energy levels, therefore, if a relay is to operate reliably during the decay period associated with these transients, signal conditioning (filtering) becomes a very important factor in the design of the relay.

C. Scheme Considerations

Thus far the discussion of relay performance has been independent of the scheme in which it is used. In general, a complete relaying scheme will include both direct tripping elements, which must not see faults beyond the end of the line, and permissive trip elements, which must overreach the line.

In a permissive trip scheme, which only requires overreaching functions, overreaching in the tripping direction is not a problem. And, as discussed in the previous paragraph, a large reach can be used on the overreaching functions to insure correct directional integrity, at least on a dynamic basis. However, directional integrity could be lost on a steady-state basis, and incorrect tripping could be initiated unless some means is included to prevent it.

Because of the above limitation in permissive tripping schemes, directional comparison hybrid and directional comparison blocking schemes have been used extensively in the protection of series compensated lines. In these schemes both tripping and blocking functions are used with the requirement that the tripping functions at one end of the line coordinate with the blocking functions at the other end for all external faults within reach of the tripping functions; i.e., the blocking functions should operate as fast as or faster than the tripping functions. To insure the fastest possible operation from the scheme, the functions should be designed to meet the above criteria so that the overall scheme logic need only incorporate enough time delay to allow for channel time plus propagation time plus a small margin, without the need for additional time to insure proper coordination of the functions.

Figure 30 illustrates by the coincidence blocks shown that a blocking function at the location shown in Figure 26 will operate on the external capacitive fault shown in Figure 26, even with a zero ohm reach. If the reach of the blocking function is increased to 18 ohms, operation becomes very reliable as indicated by the coincidence blocks shown in Figure 31.

The system of Figure 32 was set up on the model power system and will be used to show that the key to reliable operation of a hybrid or blocking scheme is the need to coordinate the trip function at one end of the line and the blocking function at the other end. The operation of a tripping function at the left end of the upper line will be compared to the operation of a blocking function at the right end. Both functions are set with a reach of 18 ohms. MOV protection was simulated because coordination is more difficult for a fault at F1 if the MOV is conducting sufficient current to make the capacitor bank appear substantially resistive. Figure 33, 34 and 35 show VOP, VPOL, and the timer input for both the tripping unit at the left end of the line and the blocking unit at the right for various load flow conditions. In the initial 20 milliseconds before the series capacitor bank in the lower line is bypassed:

a. Figure 33 shows that the blocking function will operate slightly faster than the tripping function with no load flow on the system.

b. In Figure 34, with load flow from right-to-left the blocking function will operate even faster than the tripping function.

c. In Figure 35, with left-to-right flow, the tripping function will operate slightly faster than the blocking function.

Thus, load flow can be a significant factor in the performance of the distance functions on or near series compensated lines and must be taken into account in the design of the functions to assure proper coordination.

Figure 36 illustrates the effect on the performance of the blocking function when line side potential is used as opposed to bus side potential. The system of Figure 32 is used with left to right load flow. Figure 36 shows that the blocking unit is more likely to operate faster when bus side potential is used than when line side potential is employed.

The coincidence blocks of Figures 33 through 36 also show that the tripping and blocking functions operate reliably after the capacitor bank is bypassed on the adjacent line.

PRACTICAL RELAY DESIGN

It should be noted that the preceding discussions are based on a very simple distance relay. Practical relay designs, even for application on uncompensated transmission lines, will be more complex. It is unlikely that any manufacturer would offer such an unsophisticated device as that used to illustrate the problems described in this paper. One of the more obvious aspects of the design is the type of filtering used in the operating circuit of the various functions. In addition to the transients associated with series compensated lines, the relays will be subjected to the “normal” transients associated with uncompensated lines, such as CT saturation, CVT transients, traveling waves, etc. The filtering must be designed to perform correctly for all of these conditions to provide reliable and secure protection. As the design of the functions becomes more complex, however, the analysis of their performance also becomes more complex.

RELAY SETTINGS

On series compensated lines, as well as on uncompensated lines, it is desirable to set the functions based on steady-state calculations and on readily known system data. However, on compensated lines, the performance of the functions is much more affected by the transients in the power system, thus the setting procedure becomes less precise, and greater setting margins are required to ensure a reliable application.

OTHER CONSIDERATIONS

A. Line Side versus Bus Side Potential (relative to capacitor)

On schemes requiring potential for the relays, one of the decisions a user must make is whether to locate the potential device on the line side or the bus side of the series capacitors. The following discussion assumes that either location is economically feasible, which may not be the case, particularly where series capacitors are added to an existing line.

Possibly the most significant reason for using line side potential is that the potential device is also used for coupling the carrier signal to the transmission line. By putting the coupling device on the line side of the capacitors, the wave traps can be installed between the carrier coupling device and the series capacitors, thus shielding the carrier to some extent from the noise generated when the trigger gaps are fired.

The use of bus side potential slightly improves the reliability of a distance directional comparison scheme but reduces the effectiveness of a direct tripping distance function since is must be pulled back in reach to prevent it from operating on a remote bus fault when the capacitor is in service. As a consequence, any pullback in the reach of the direct trip functions will result in less of the line being covered in the event that the channel is lost.

Bus side potential permits the use of simple directional functions whereas line side potential requires that the functions be compensated. However, if bus side potential is used, any system disturbance that could cause one or two phases of the bank to be bypassed, would create a dissymmetry in the line. This would appear as an internal fault to the directional functions due to the load flow over the line. Thus, when bus side potential is used, the overcurrent functions that are controlled by the directional functions must be desensitized to prevent misoperations on maximum load flow in the event a dissymmetry occurs.

B. Distance/Directional Schemes versus Current only Schemes

Schemes that use potential are generally more complex and more difficult to evaluate analytically than are schemes that use current only. However, in practice, the transients associated with series compensated lines warrant evaluating all schemes on a model power system. Thus the simplicity of the current only schemes is of limited practical value.

The major advantage of using potential in a relay scheme (and particularly distance relays schemes) is the substantial reduction in response to external faults. Thus the probability of false tripping on external faults with erroneous trip outputs from the channel is greatly reduced.

Ground distance relays become less and less dependable as the probability of high fault resistance increases. Where high resistance faults are a significant consideration then the choice is between current only schemes and directional overcurrent schemes. The directional schemes have an advantage in terms of security over the current only schemes in that they can detect external faults immediately and be made to set up transient blocking. Secondly, zero sequence current (rather than positive sequence, negative sequence, or phase current) can be used which in general will be less sensitive to external faults.

To achieve good dependability on internal faults, some form of direct trip functions are required in the event of channel failure. In general (and particularly where line side potential is used) distance functions are much more effective than overcurrent functions for interphase faults. Because series compensated lines tend to be long lines, zero sequence overcurrent functions tend to be superior for single-line-to-ground faults.

C. System Speed of Operation

The operating time of a relay system can have a significant impact on the overall reliability of the power system. Thus the user can have a positive influence on the reliability by specifying appropriate operating times.

On close-in, high current faults, very fast operation of the relay system is very desirable in view of the probability of CT saturation and the possible effects of the fault on system stability. High speed clearing of close-in faults also enhances the security of relay systems on adjacent lines by limiting the time that these systems perform to prevent operation during the fault.

Conversely, if fast operating time is specified for remote, lower current faults, the more likely a false trip is to occur before an external fault is cleared. Greater use of direct transfer trip channels can often improve the speed on remote end faults without degrading the security during external faults.

D. Channel Selection

Channel selection should be related to the type of relay scheme selected. If the scheme is very dependent on the correct operation of the channel, then a highly reliable channel should be selected. Conversely, if the relay scheme has minimum dependence on the channel, then a lower reliability channel may still give acceptable performance.

If the relay scheme has a tendency to see faults over a large area of the power system, then a very secure channel should be selected.

E. Choice of Protection

In general, where two protective schemes are used, the choice of different schemes may tend to degrade the overall security of the line protection. Thus the gain in dependability of using different designs must more than of offset the loss in security if a net gain in reliability is to be achieved. If different schemes are used they should be examined for areas of possible weakness to insure the schemes are complementary. That is, where one scheme exhibits an area of weakness, the other scheme should exhibit an area of strength.

SCHEME AND RELAY EVALUATION

A. Analog versus Digital Model Power Systems

Analog Model Power Systems were developed over twenty years ago for use by both the manufacturer and user in the development and evaluation of protective relays and systems. These model power systems are required to study the effects of the transient and steady-state problems associated with both compensated and uncompensated lines. Recent developments have led to the use of digital model power systems based on EMTP studies.

The analog system is very flexible, permitting rapid testing over a wide range of parameters, such as load flow, source to line impedance ratio, fault incidence angle, protection level, etc. Many cases can be ran in a short period of time, thus permitting the number of cases to be evaluated to be several orders of magnitude greater than can be done with a digital system over the same time period. Thus the analog system allows the most onerous cases (worst fault incidence angle for example) to be easily determined simply by monitoring the relay response as the multiple cases are being run. This is vitally important in the development of a relay system, since different applications will encompass a wide range of system parameters.

The digital system has the advantage of being capable of simulating a larger part of the power system with much greater precision than is practical with an analog system. It provides an ideal approach to duplicating the effects of an isolated incident that may have resulted in a questionable relay operation. The digital system requires considerable insight into the response of the power system and the relay system in selecting cases to be used in making an evaluation if meaningful results are to be produced.

FIELD EXPERIENCE

The initial application of protection to series compensated lines occurred at about the time of the widespread development of model power systems as a tool for relay development. The initial relay systems were largely phase comparison systems due to the apparent difficulties of applying distance relays on series compensated lines. Some of the phase comparison systems went into service before model power systems were available to aid in the design and evaluation. The poor performance of the initial relay systems which were developed and applied solely from analytical studies emphatically demonstrated the need for design confirmation on a model power system. Thus the experience record of the initial systems is not pertinent to the present state of the art where it is presumed that all relay systems have been developed and/or confirmed on some form of model power system. Unfortunately, published experience records of the performance of relays on series compensated lines is sketchy, at best.

The company with which the authors are associated has sold hundreds of terminals of relay systems for use on series compensated lines. Based on feedback from the field:

a. The majority of problems have been channel related.

b. The next largest group of problems have been caused by human error. It should be noted that some of the human errors may be related to the more sophisticated designs and more complicated application rules encountered in applying protection to series compensated lines.

c. A smaller group of problems are related to component failures.

d. An insignificant percentage of problems has been directly related to the series capacitors in the lines.

e. Failure of a relay to trip were negligible except in those cases where channel problems prevented the system from tripping properly.

SUMMARY

In general, the problems associated with the protection of series compensated lines become less and less significant as the fault capacity on the bus increases. Thus testing under minimum system conditions will tend to provide more onerous test cases than would testing under maximum system conditions.

The better the appreciation of the problems of series compensated lines, the more likely evaluation tests on a model power system will yield meaningful results.

When the relaying system has been properly developed on a model power system, field experience indicates the presence of series capacitors will have an insignificant effect on overall system reliability when compared with other factors, most notably channel performance.

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3. A. L. Coutrs and E. C. Starr, Experience with 500kV Series Capacitor Installations and New Protection Schemes on the BPA System, *CIGRE 31-09*, 1980.

4. J. R. Homann, S. A. Miske, Jr., I. B. Johnson, A. L. Courts, "A Zinc Oxide Varistor Protection System for Series Capacitors," *IEEE Transactions on Power Apparatus and Systems*, Vol. PA5-100, 1981 PP 929-937.

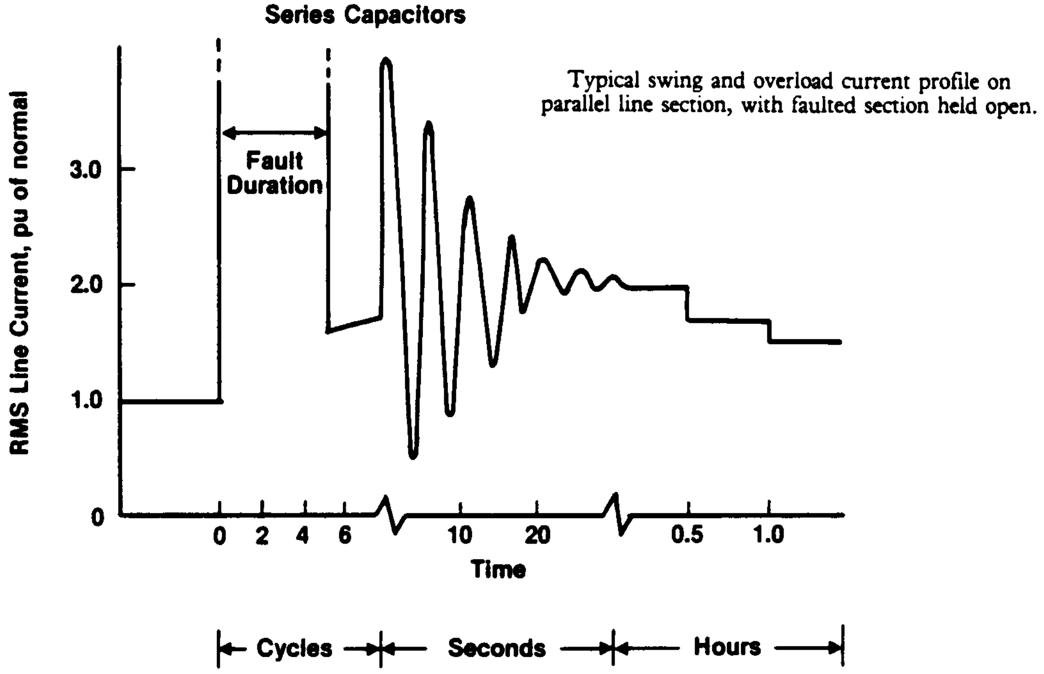
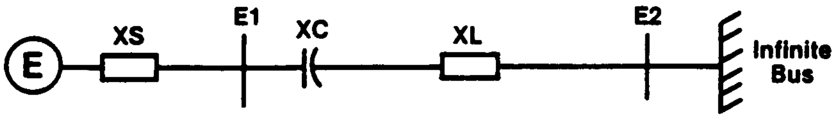
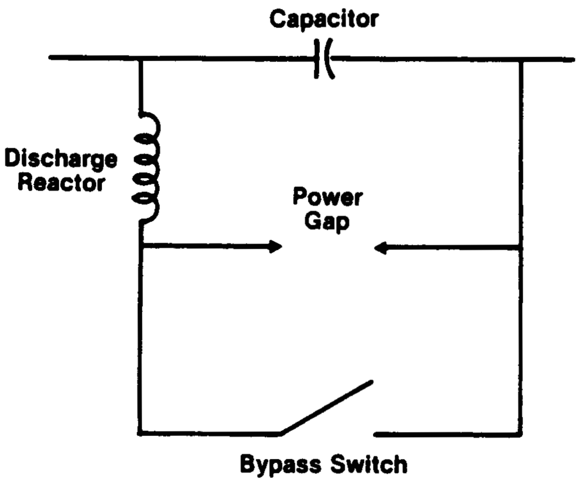


Figure 1



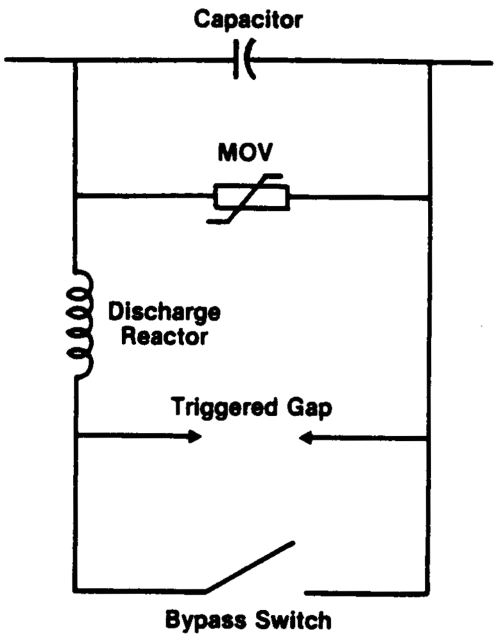
Simplified System

Figure 2



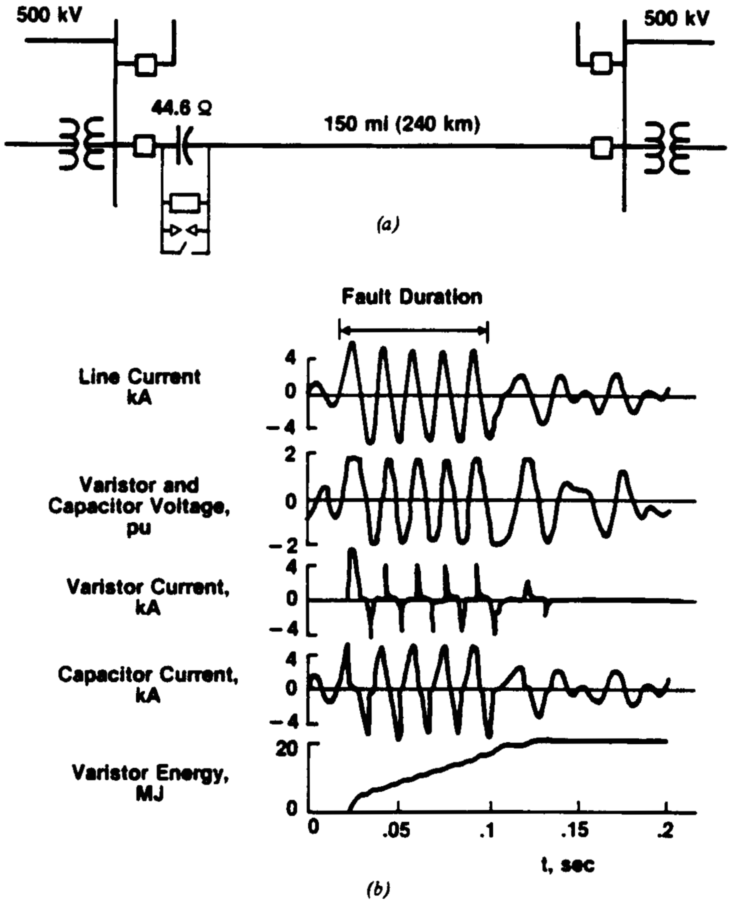
Parallel Power Gap

Figure 3



Metal Oxide Varistor

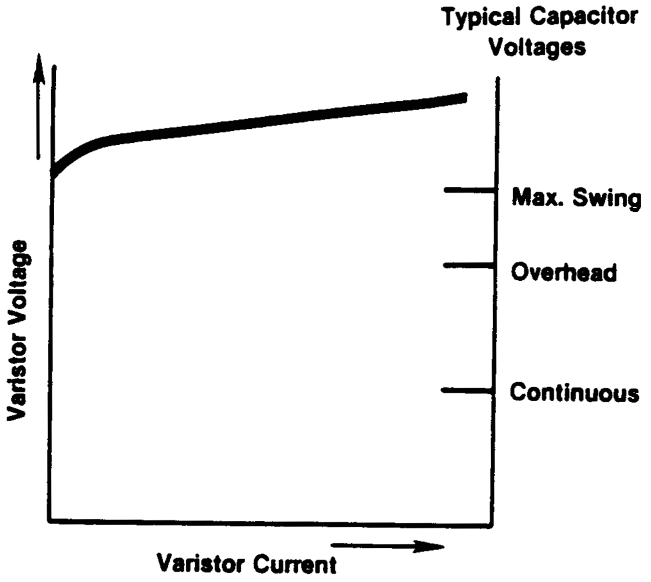
Figure 4



(a) 500-kV circuit with a three-phase fault external to the compensated line

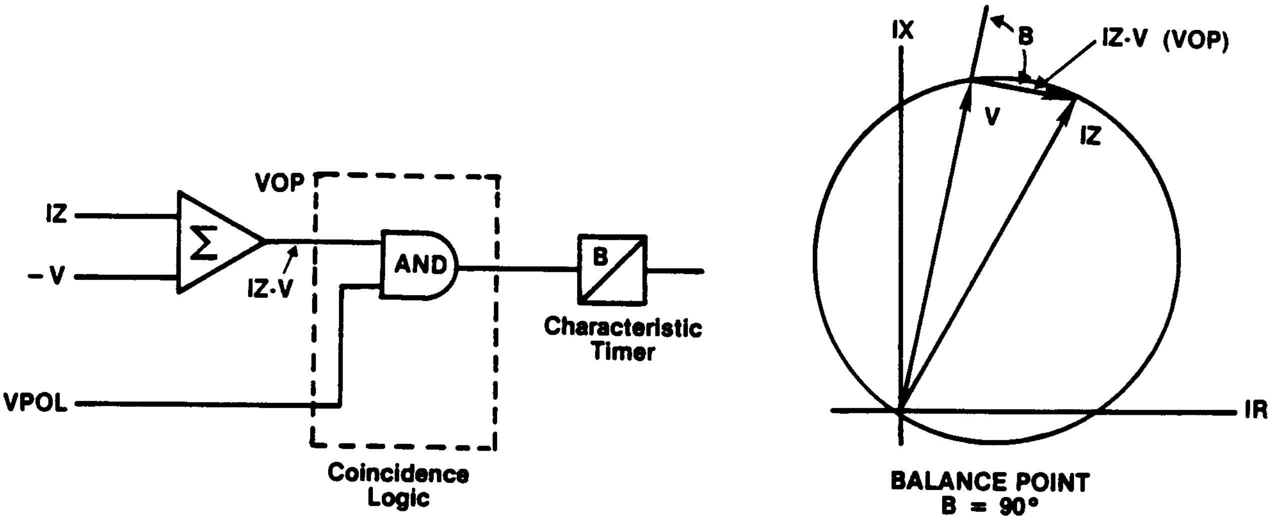
(b) Voltage and current waveforms for a five-cycle fault on the circuit of (*a*).

Figure 5



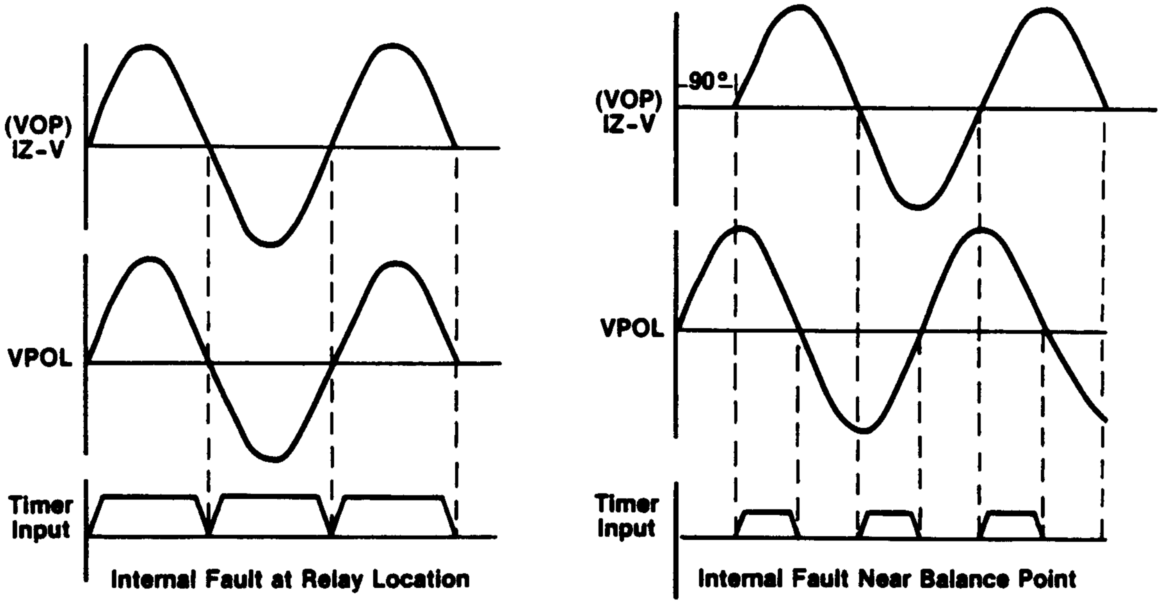
Voltage/current characteristic of varistor. © 1980 IEEE.

Figure 6



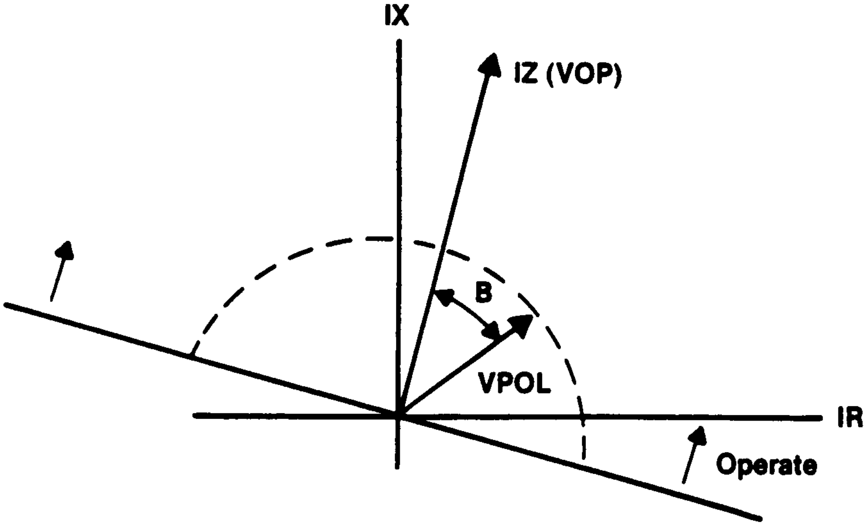
a. Simple Phase Angle Comparer

b. Mho Characteristic



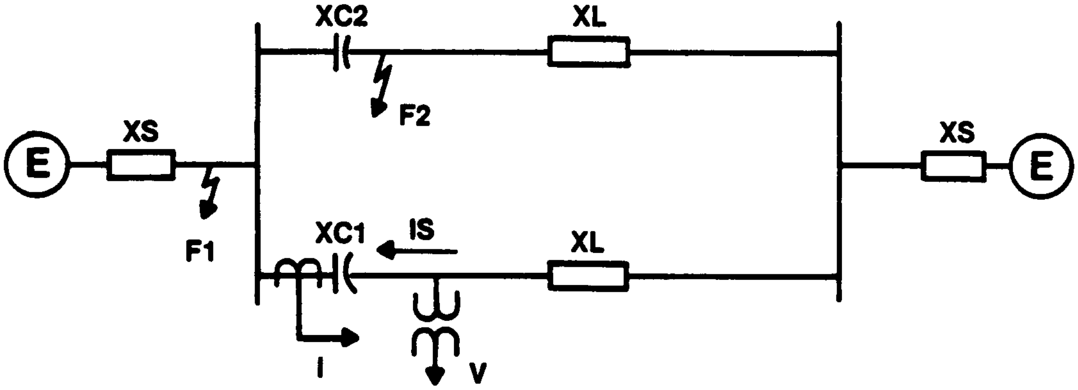
c. Typical Timer Inputs

Figure 7

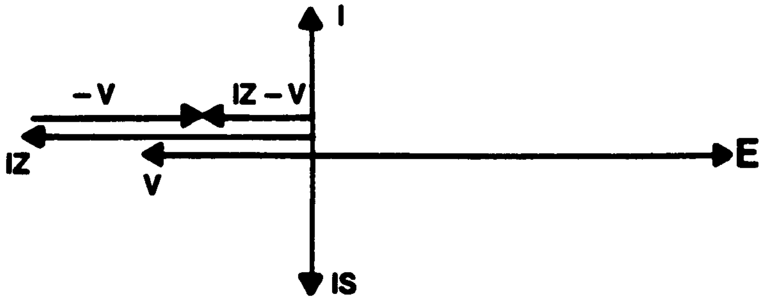


Phasor Diagram for Simple Directional Function

Figure 8

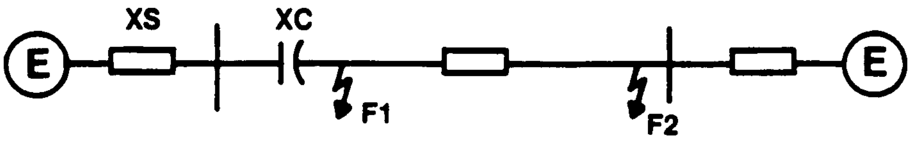


a. Typical System

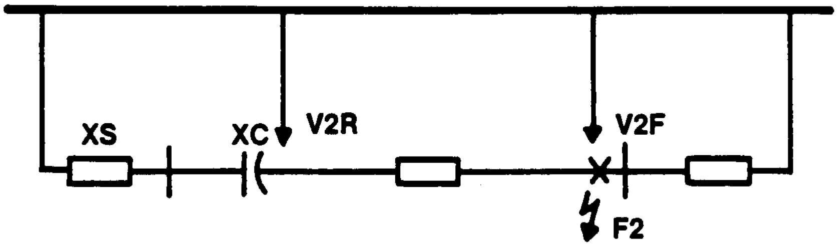


b. Typical Phasor Diagram, Fault at F1

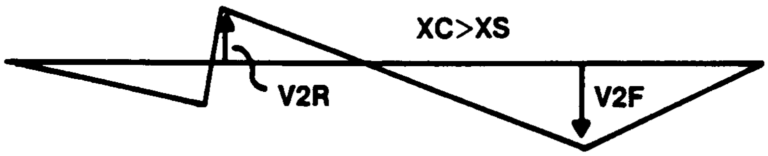
Figure 9



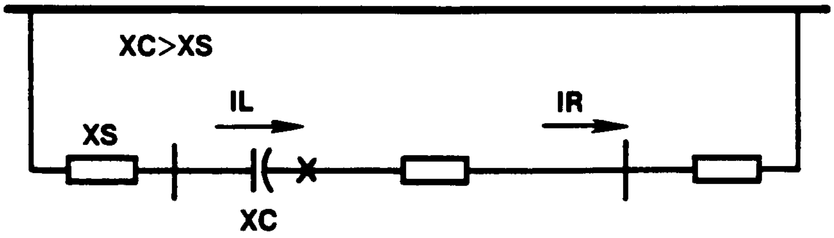
a. Typical System



b. Negative Sequence Network

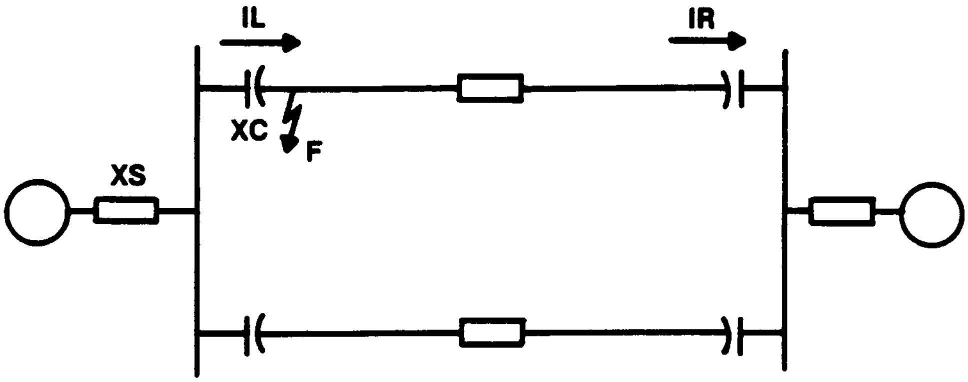


c. Voltage Profile for Fault at F2



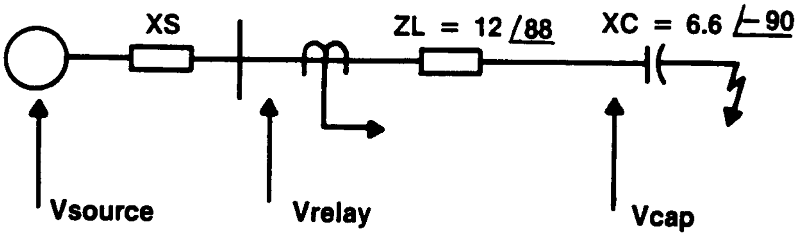
d. Current Distribution for Fault at FI

Figure 10



Typical System

Figure 11



a. Simple System

Figure 12

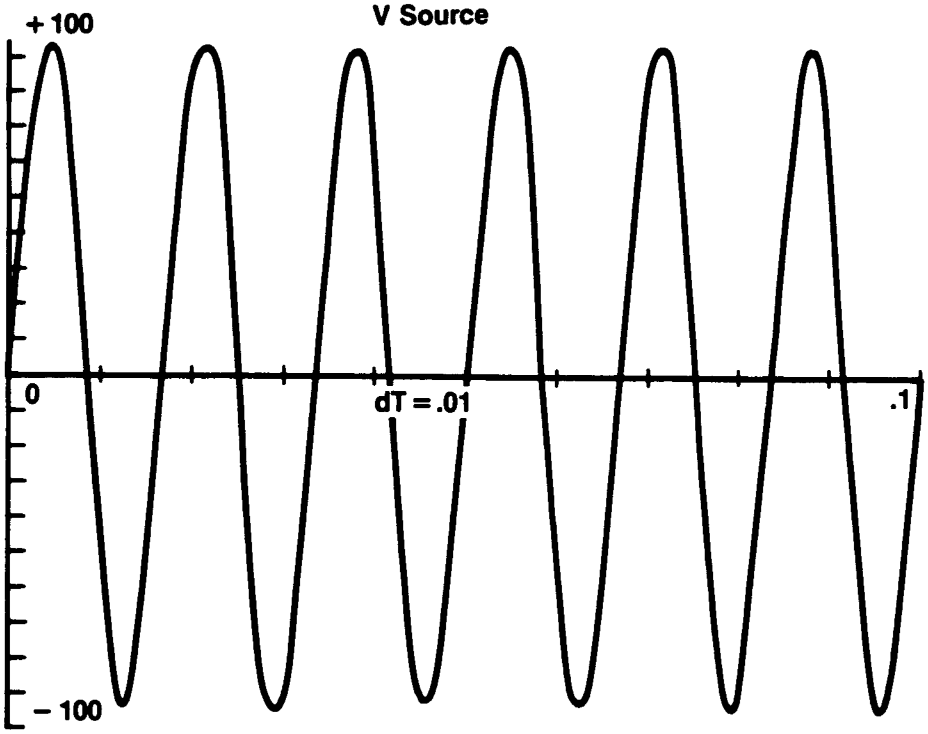


Figure 13

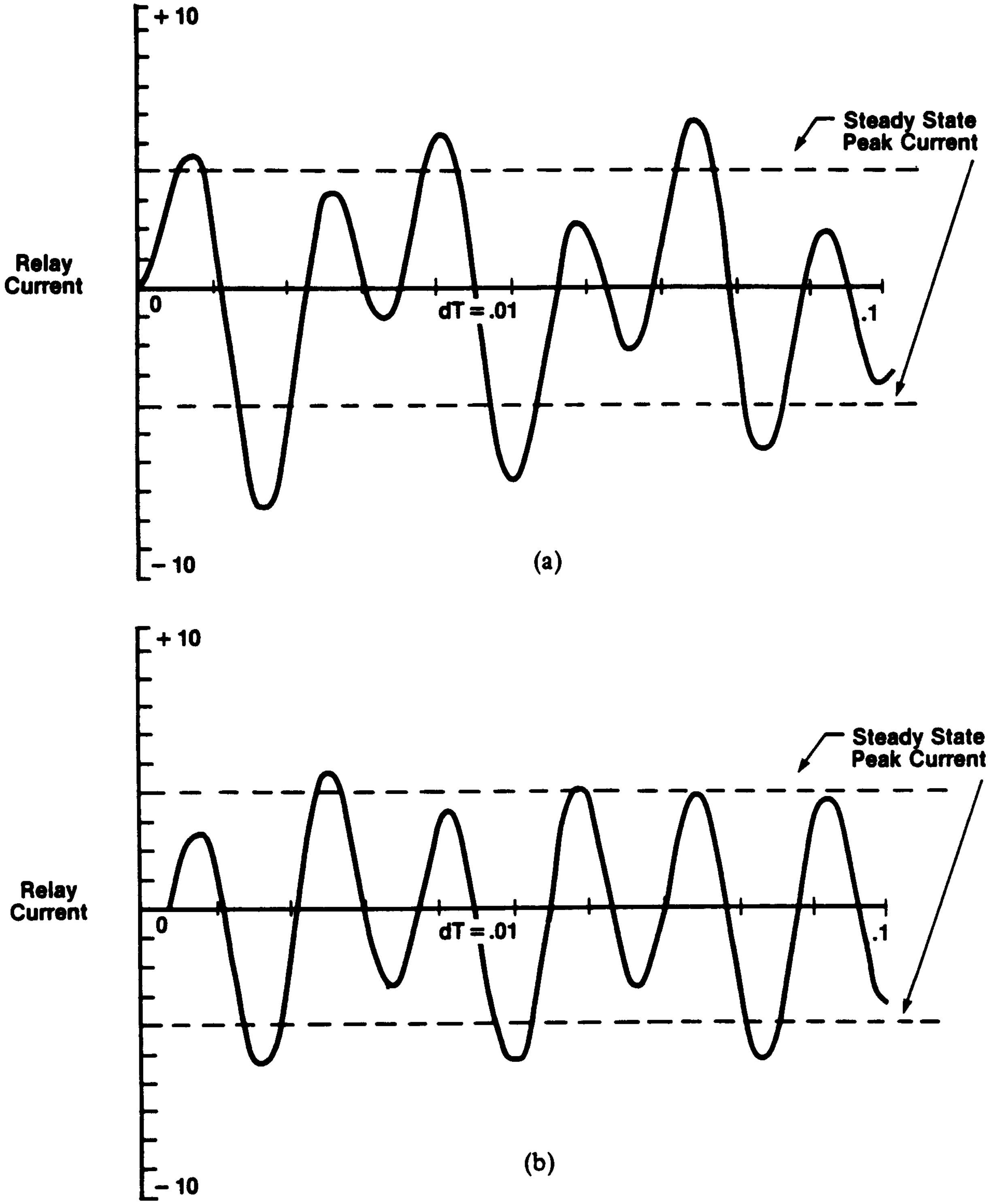

+ 10
Relay Current
0
dT = .01
.1
Steady State Peak Current
– 10
(a)
+ 10
Relay Current
0
dT = .01
.1
Steady State Peak Current
– 10
(b)

Figure 14

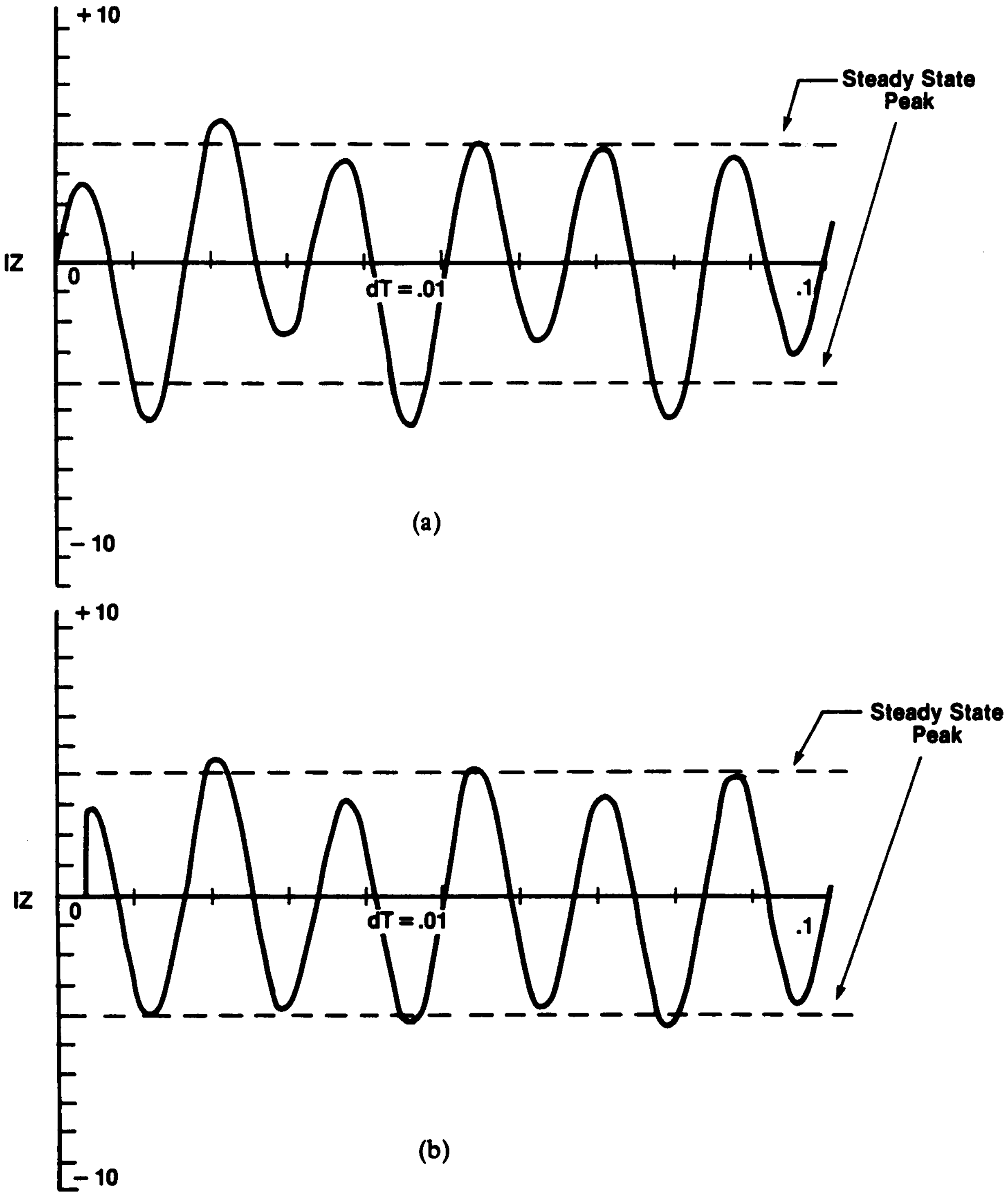

+10
Steady State Peak
IZ
0
dT = .01
.1
-10
(a)
+10
Steady State Peak
IZ
0
dT = .01
.1
-10
(b)

Figure 15

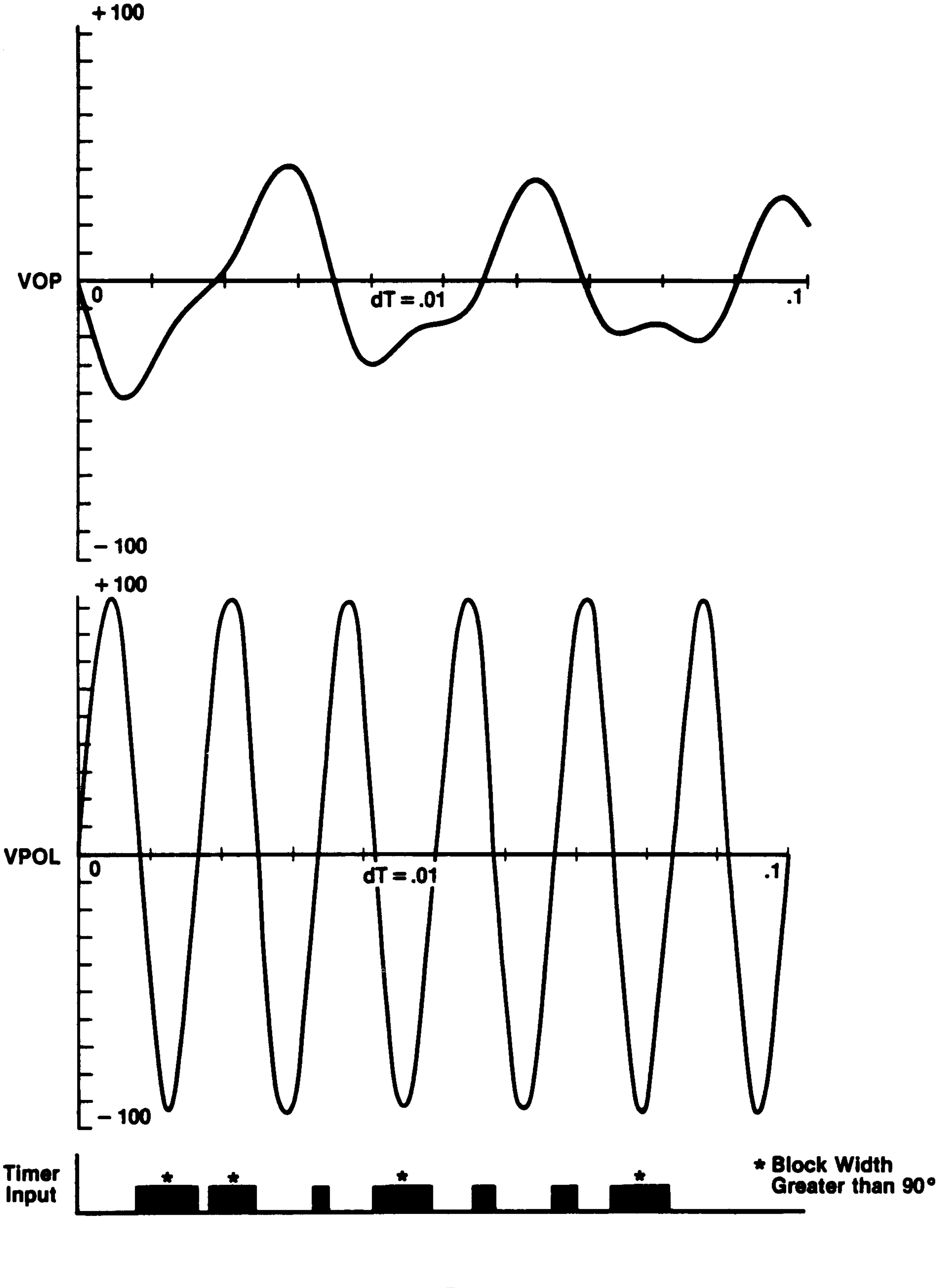

+100
VOP
0
dT = .01
.1
− 100
+100
VPOL
0
dT = .01
.1
− 100
Timer Input
* Block Width Greater than 90°

Figure 16

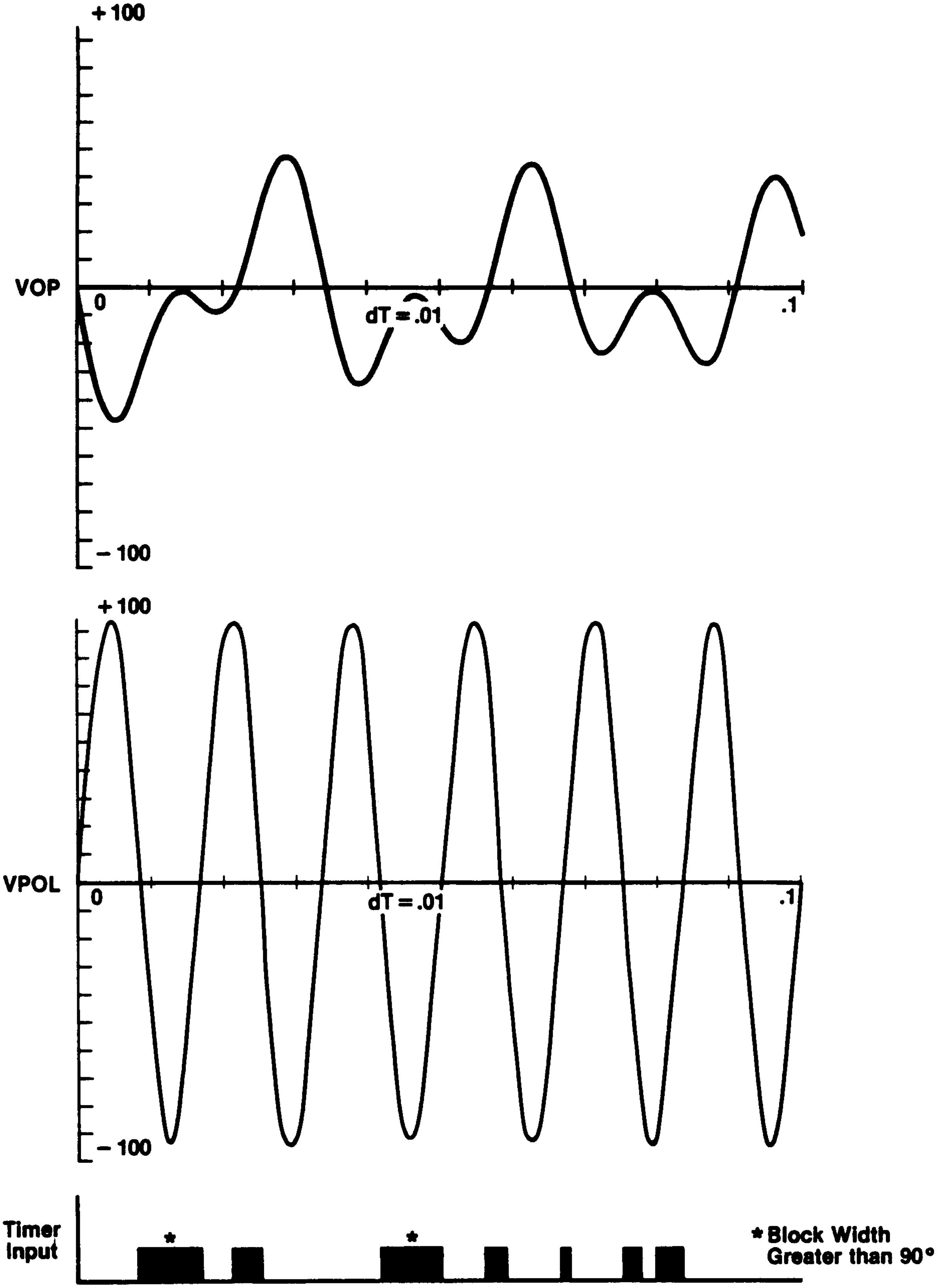

+100
VOP
0
dT = .01
.1
−100
+100
VPOL
0
dT = .01
.1
−100
Timer Input
*
*
* Block Width Greater than 90°

Figure 17

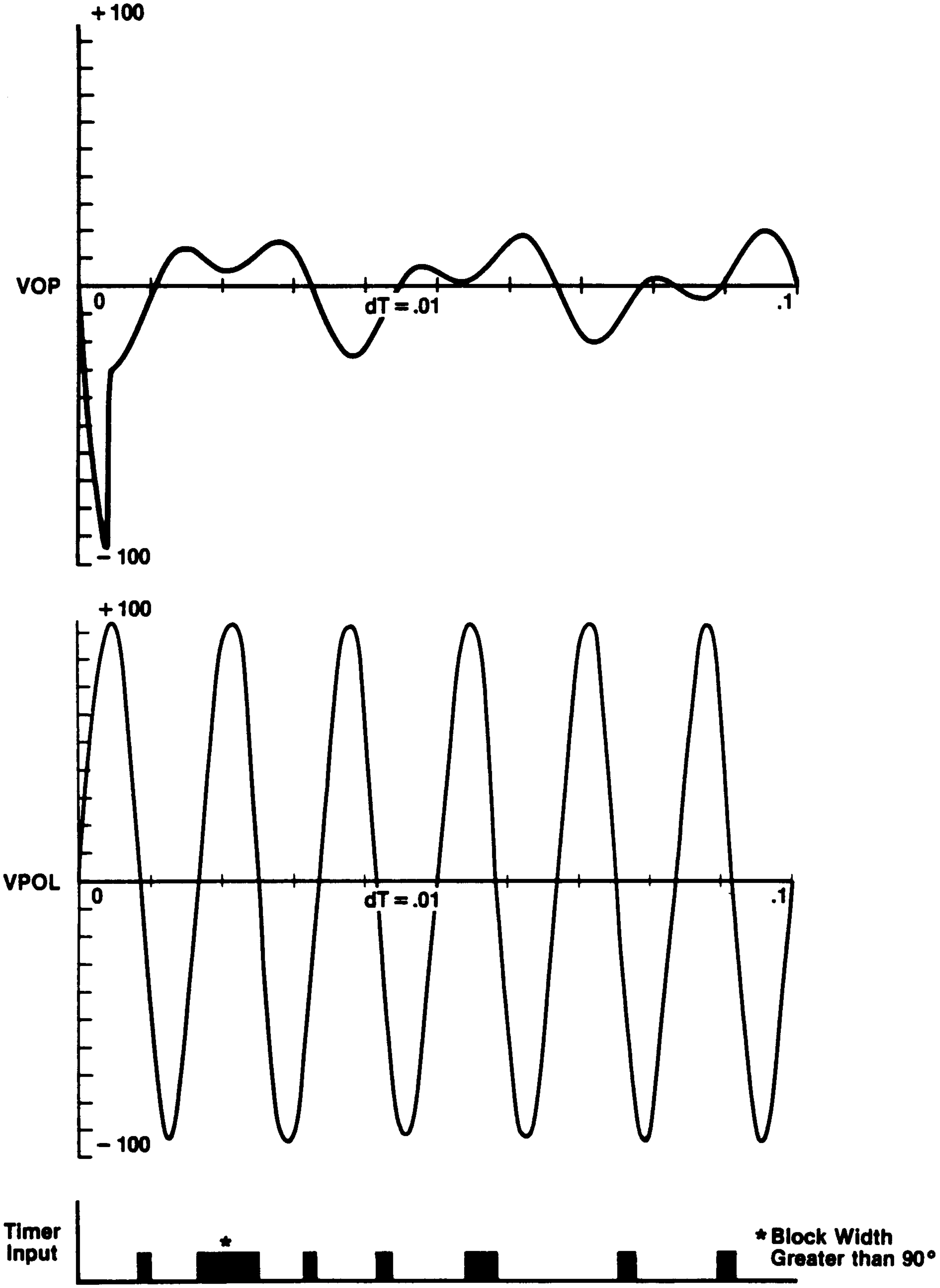
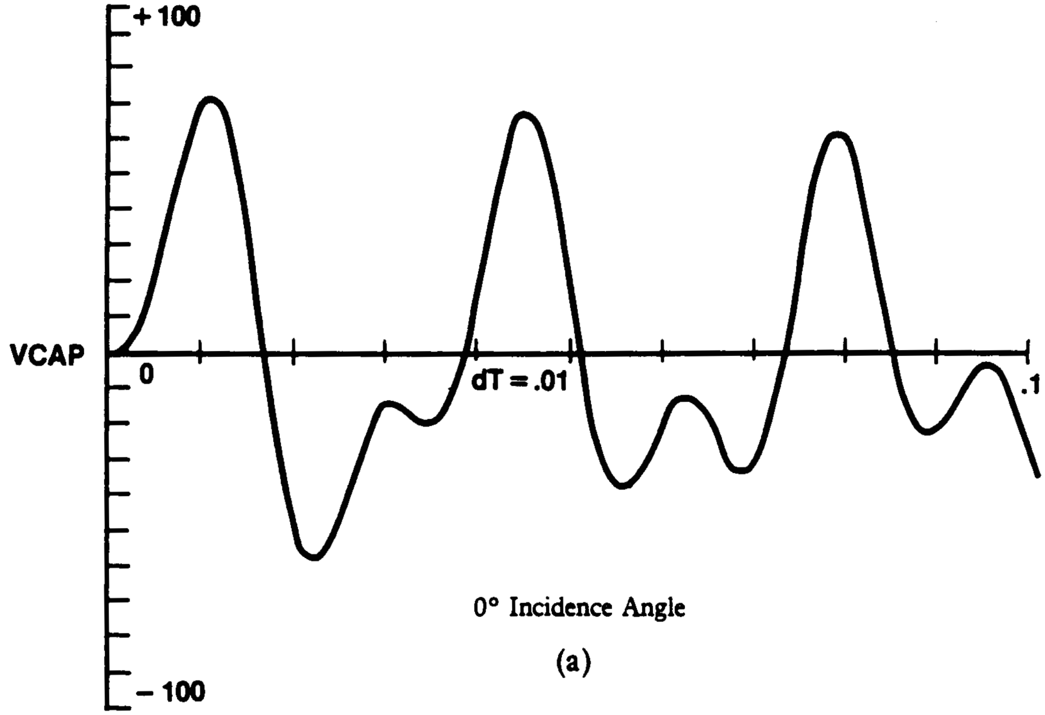
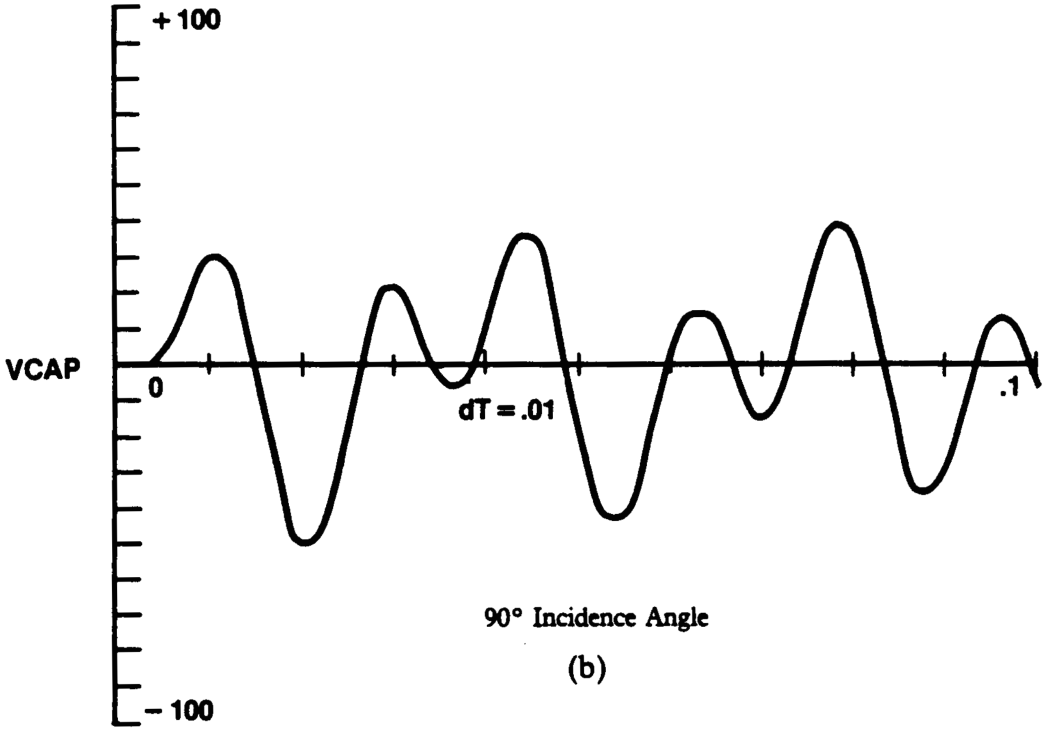

+100
VOP
0
dT = .01
.1
−100
+100
VPOL
0
dT = .01
.1
−100
Timer Input
*
* Block Width Greater than 90°

Figure 18



0° Incidence Angle

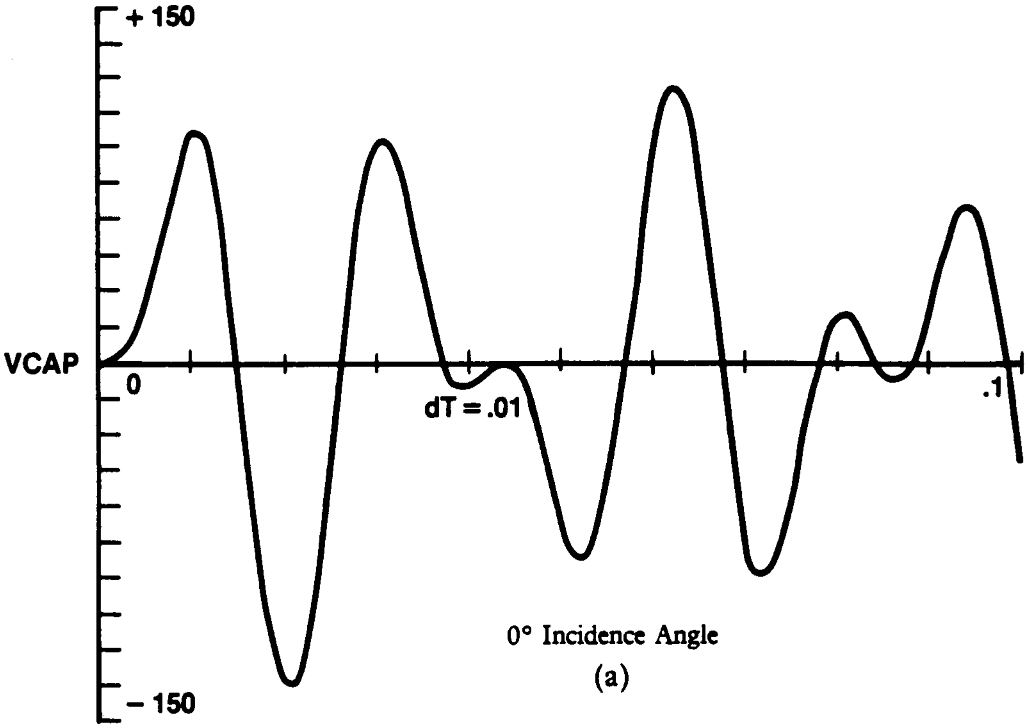
(a)



90° Incidence Angle

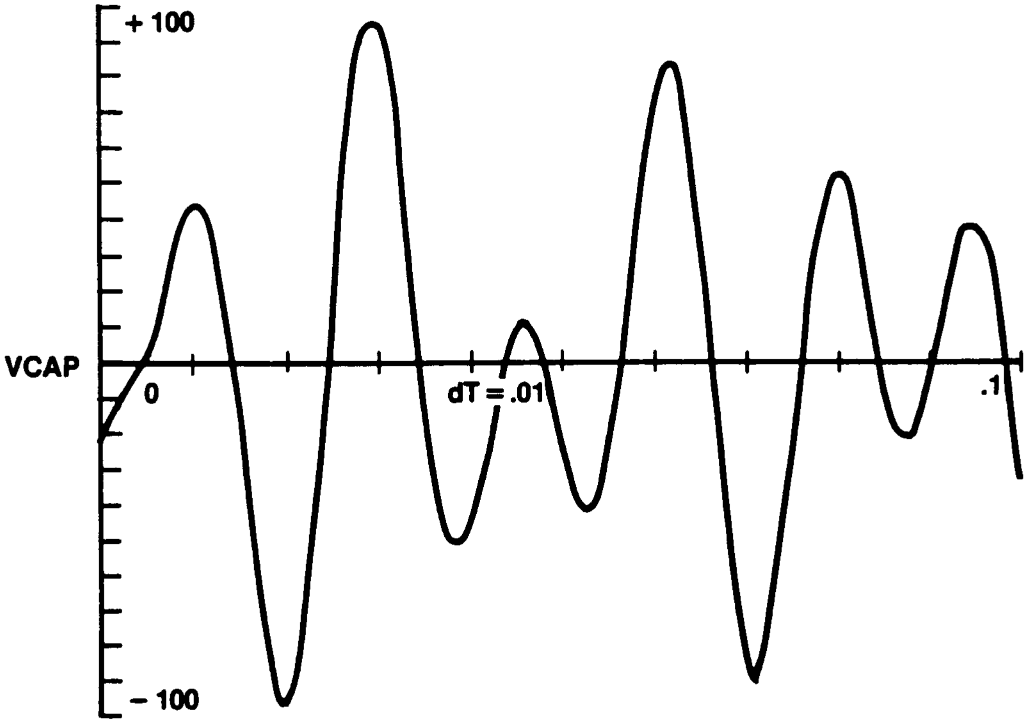
(b)

Figure 19



0° Incidence Angle

(a)



90° Incidence Angle

(b)

Figure 20

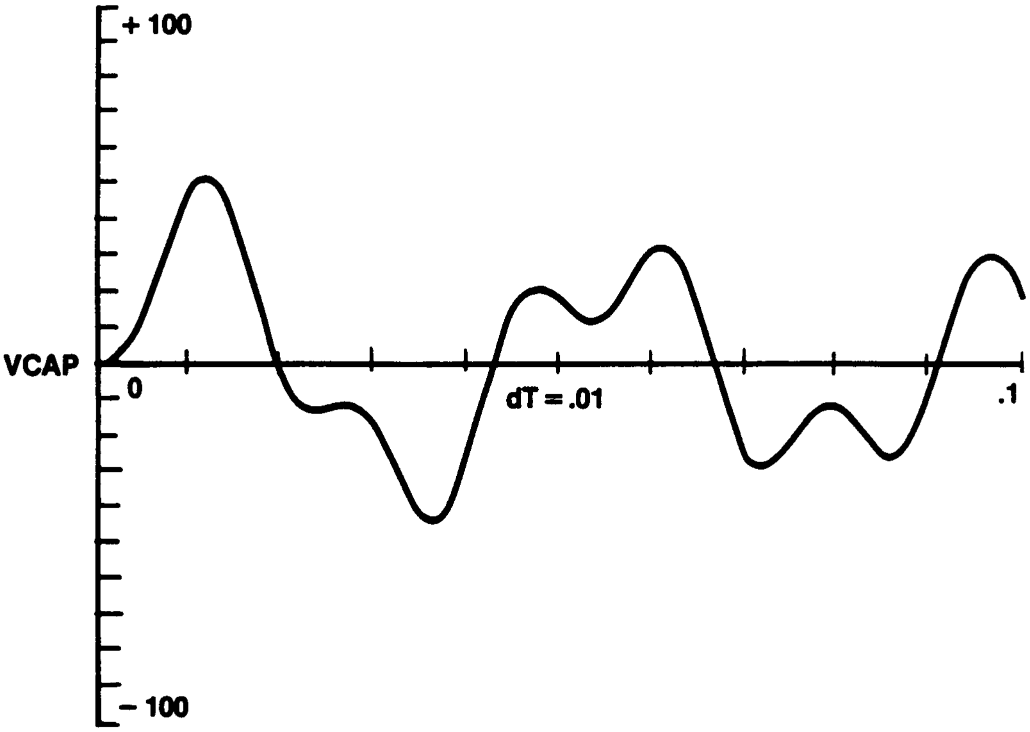


Figure 21

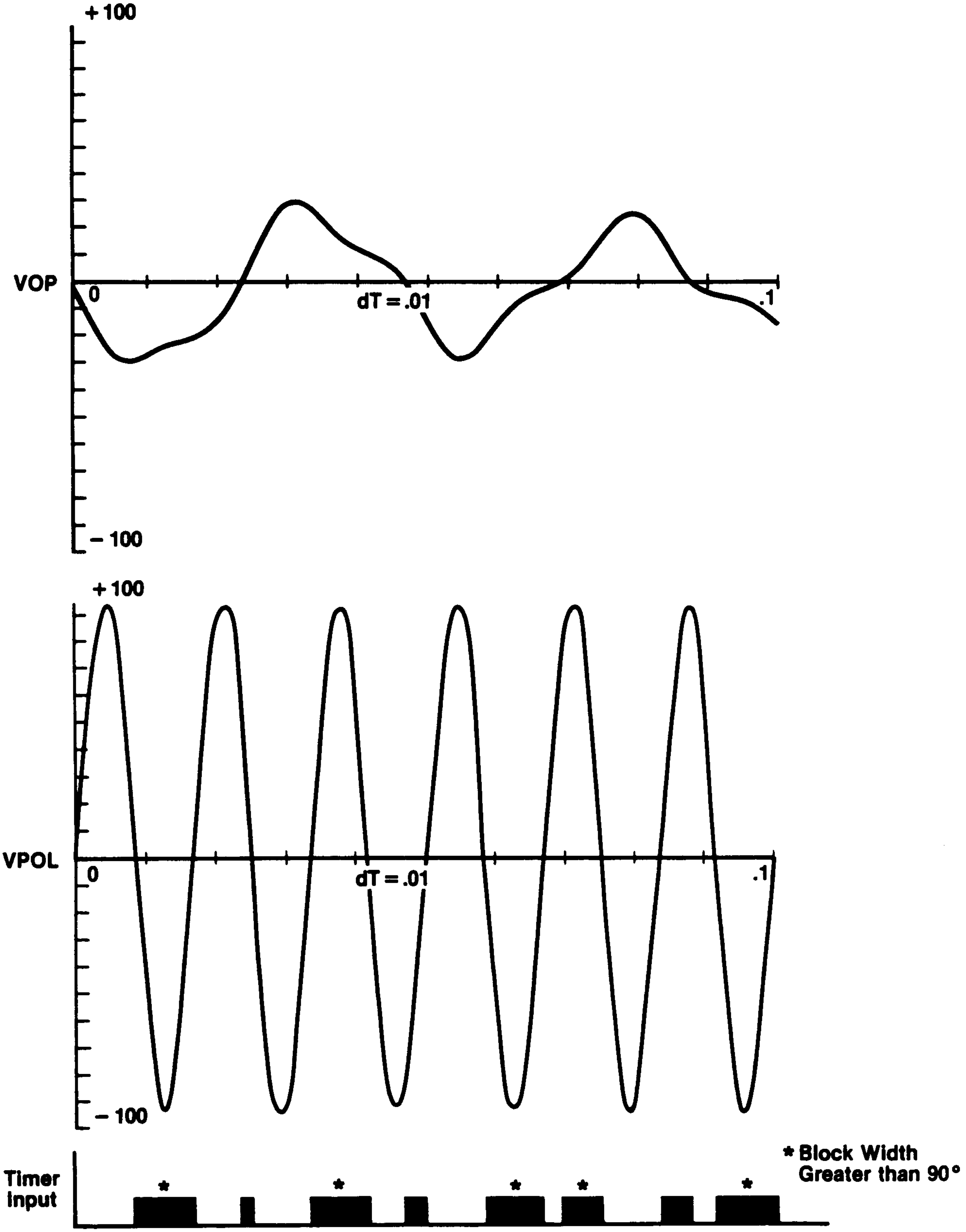

+100
VOP
0
dT = .01
.1
−100
+100
VPOL
0
dT = .01
.1
−100
Timer Input
* * * * *
* Block Width Greater than 90°

Figure 22

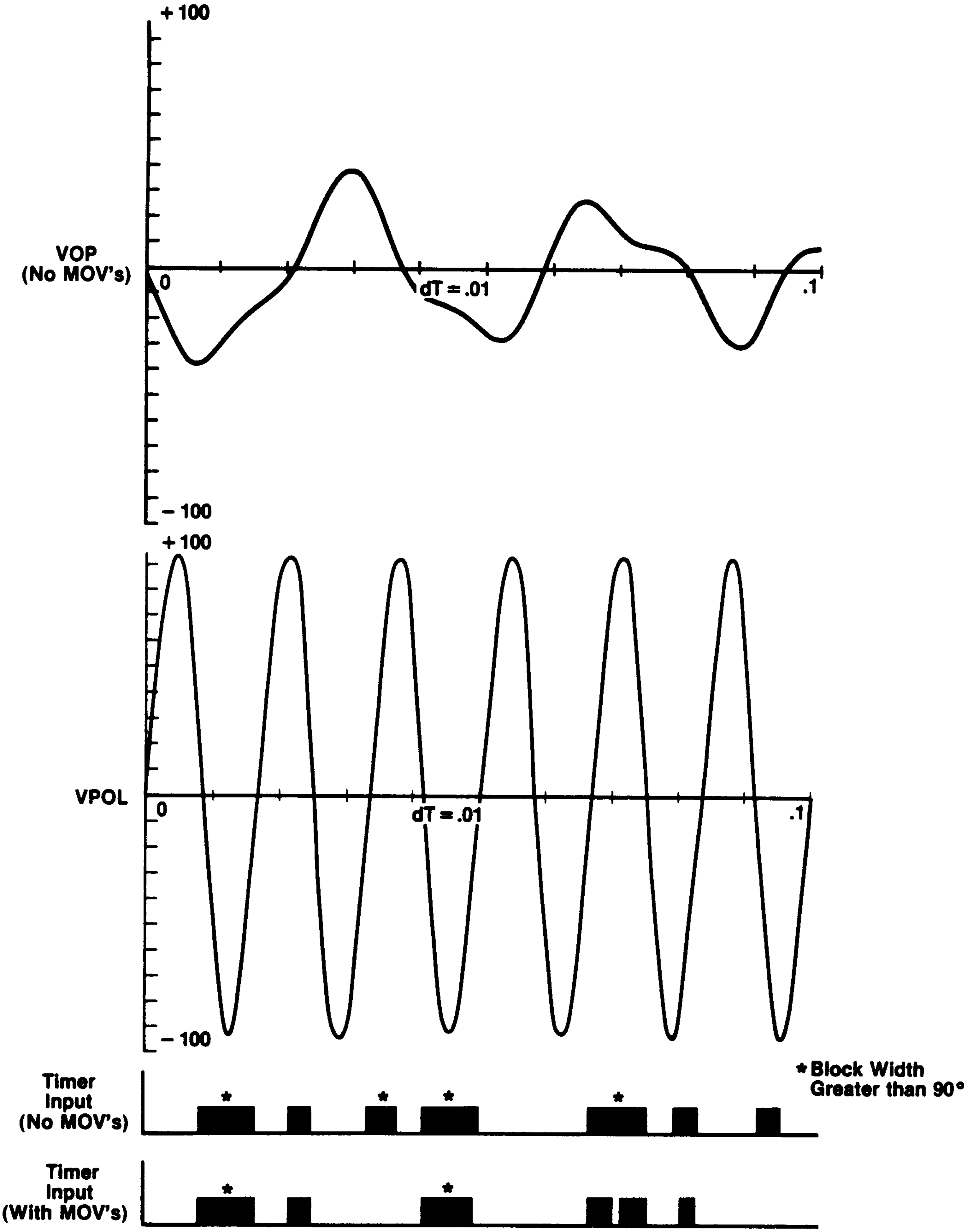

+100
VOP
(No MOV's)
0
dT = .01
.1
−100
+100
VPOL
0
dT = .01
.1
−100
Timer
Input
(No MOV's)
*
*
*
*
* Block Width
Greater than 90°
Timer
Input
(With MOV's)
*
*

Figure 23

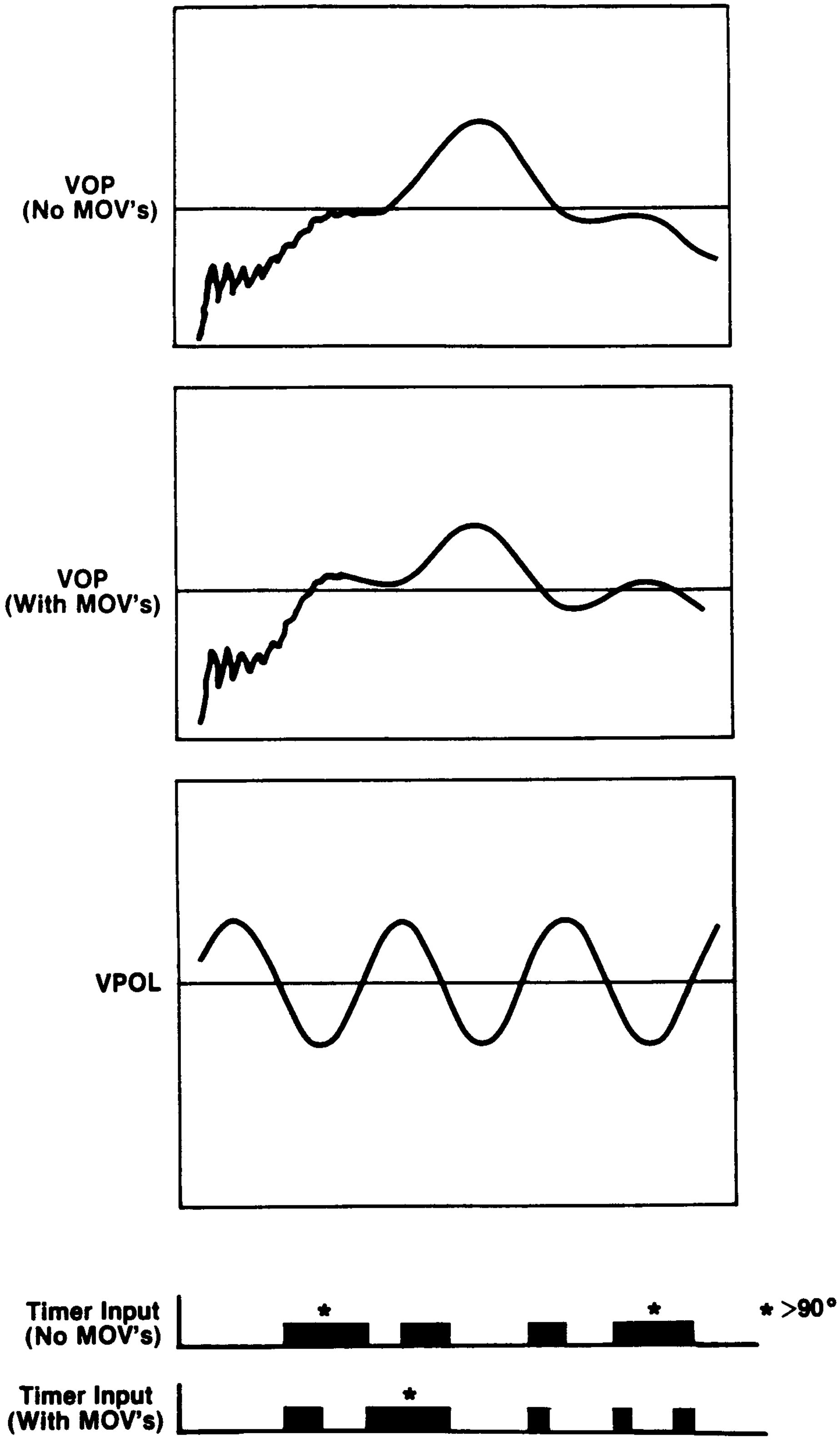
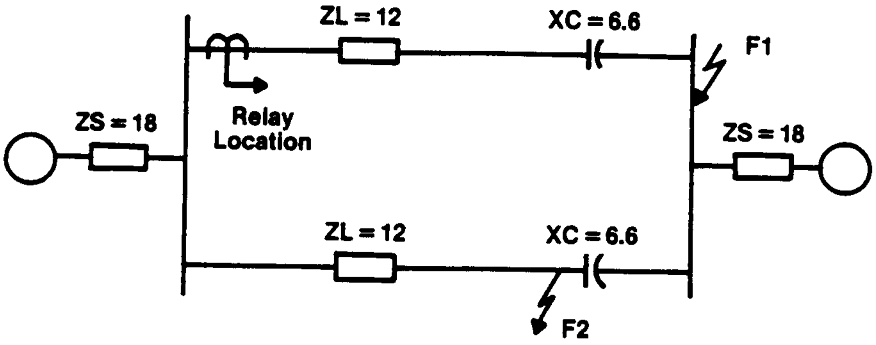
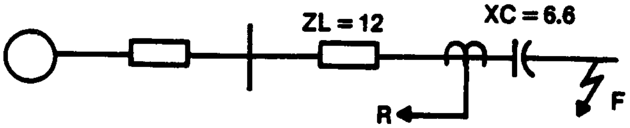

VOP
(No MOV's)
VOP
(With MOV's)
VPOL
Timer Input
(No MOV's)
Timer Input
(With MOV's)
* >90°

Figure 24



Typical System

Figure 25



Typical System

Figure 26

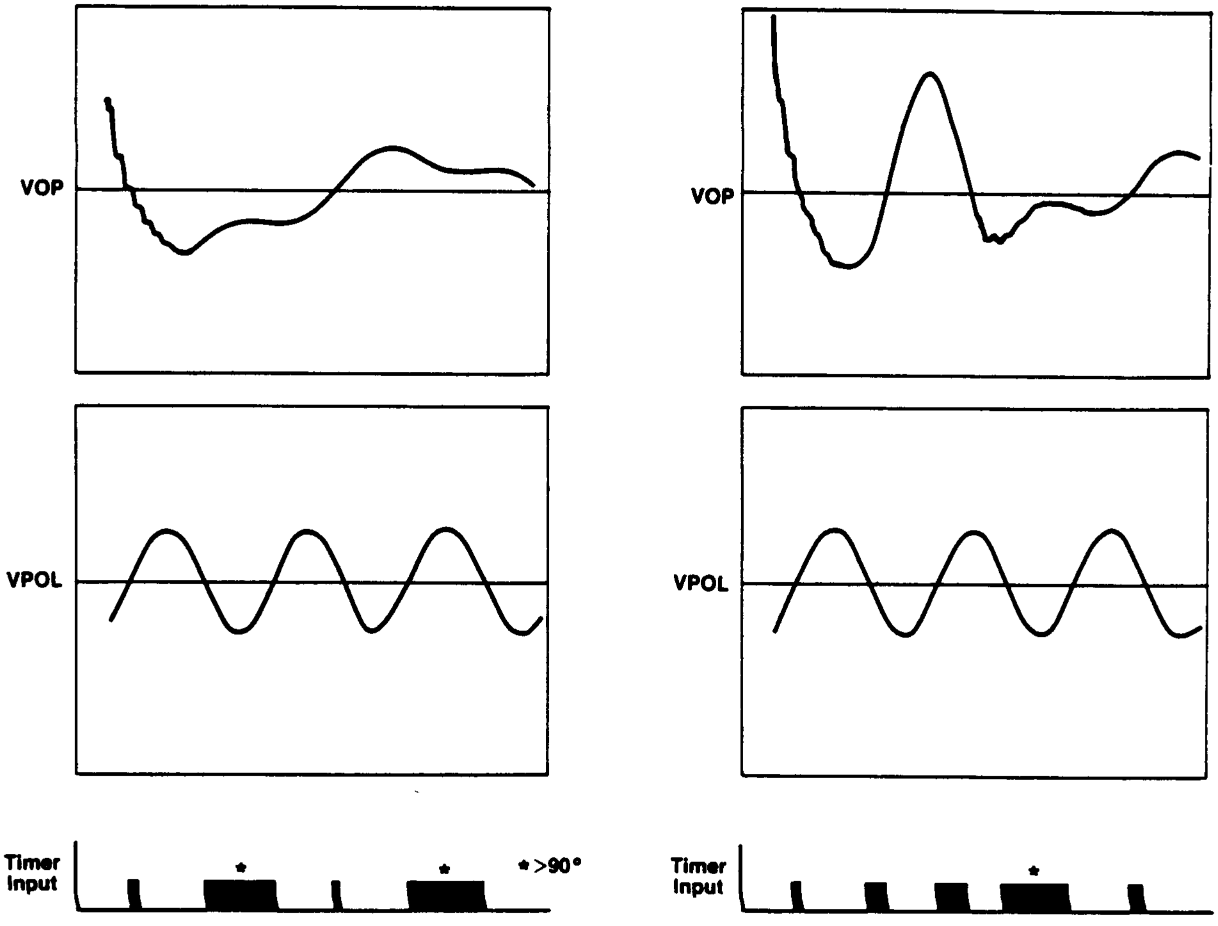


Figure 27

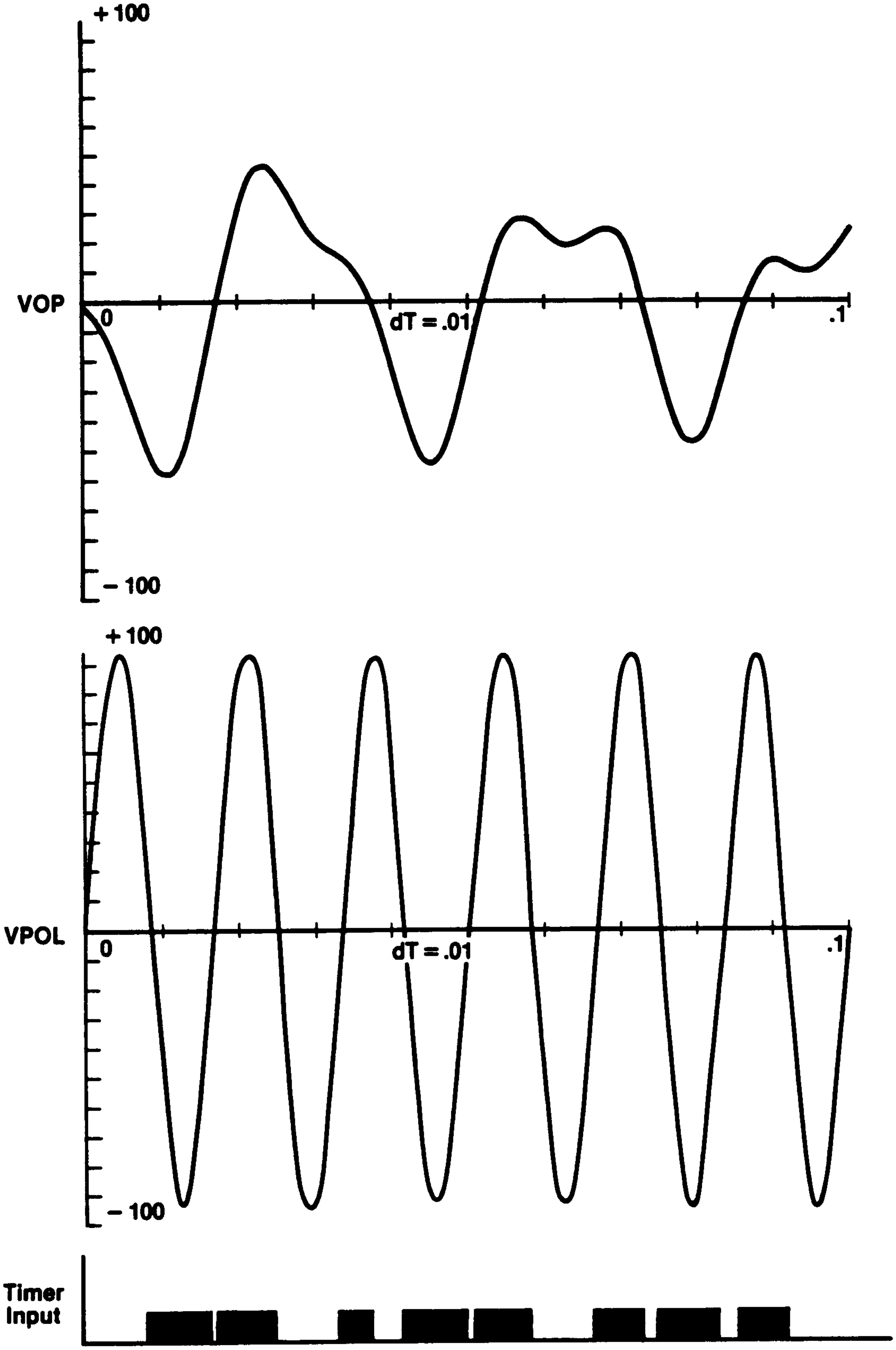


Figure 28

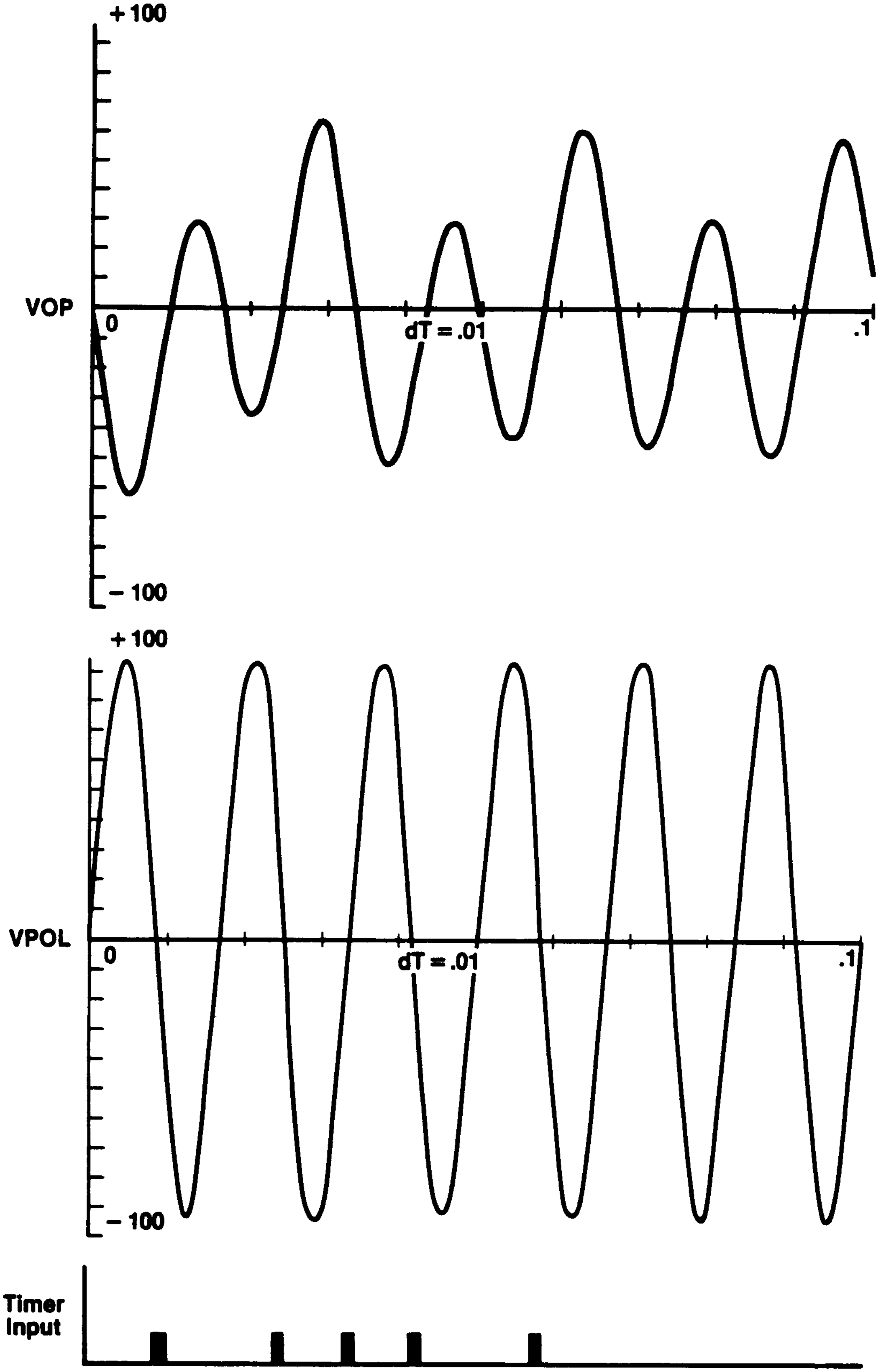


Figure 29

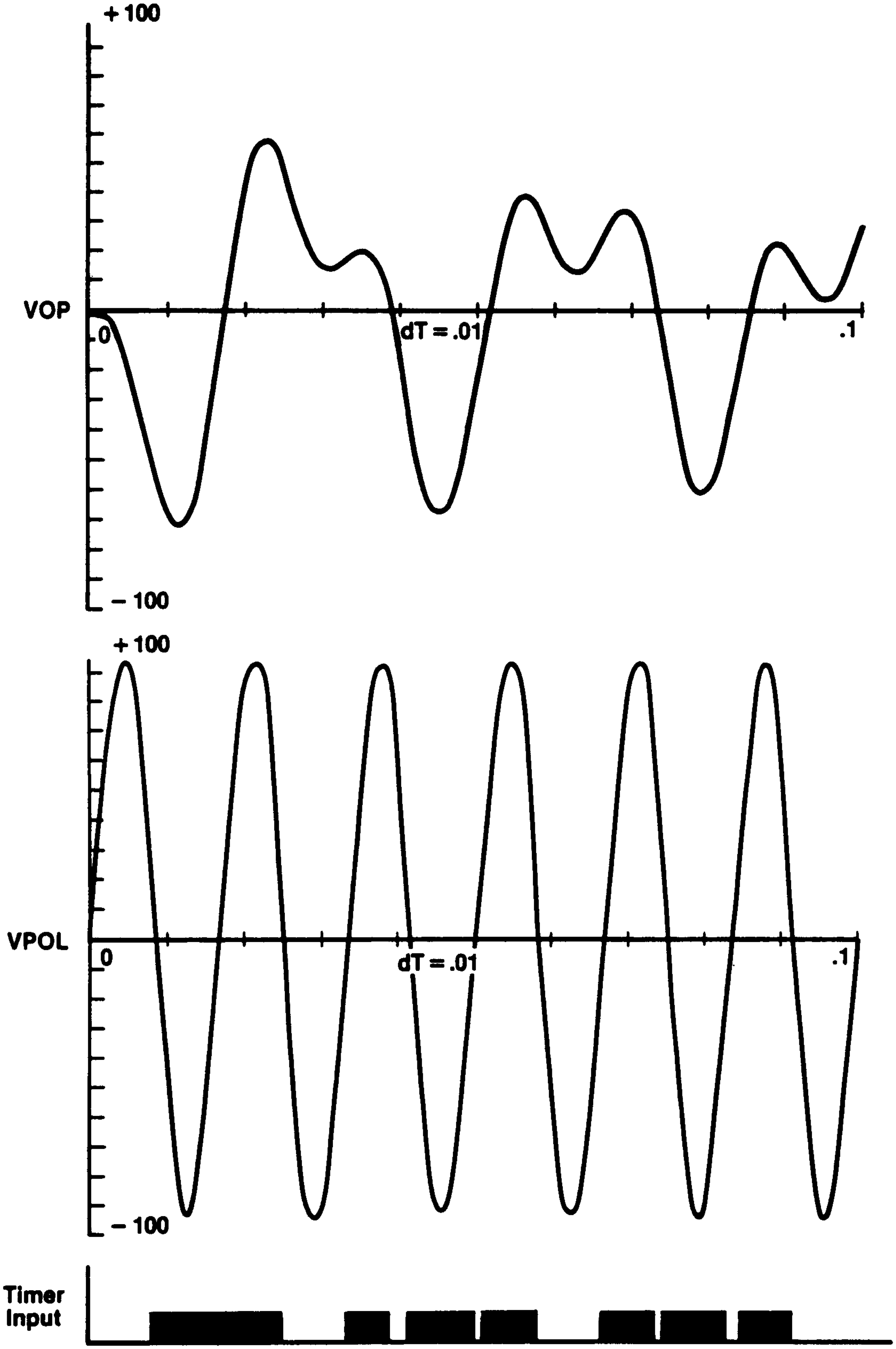


Figure 30

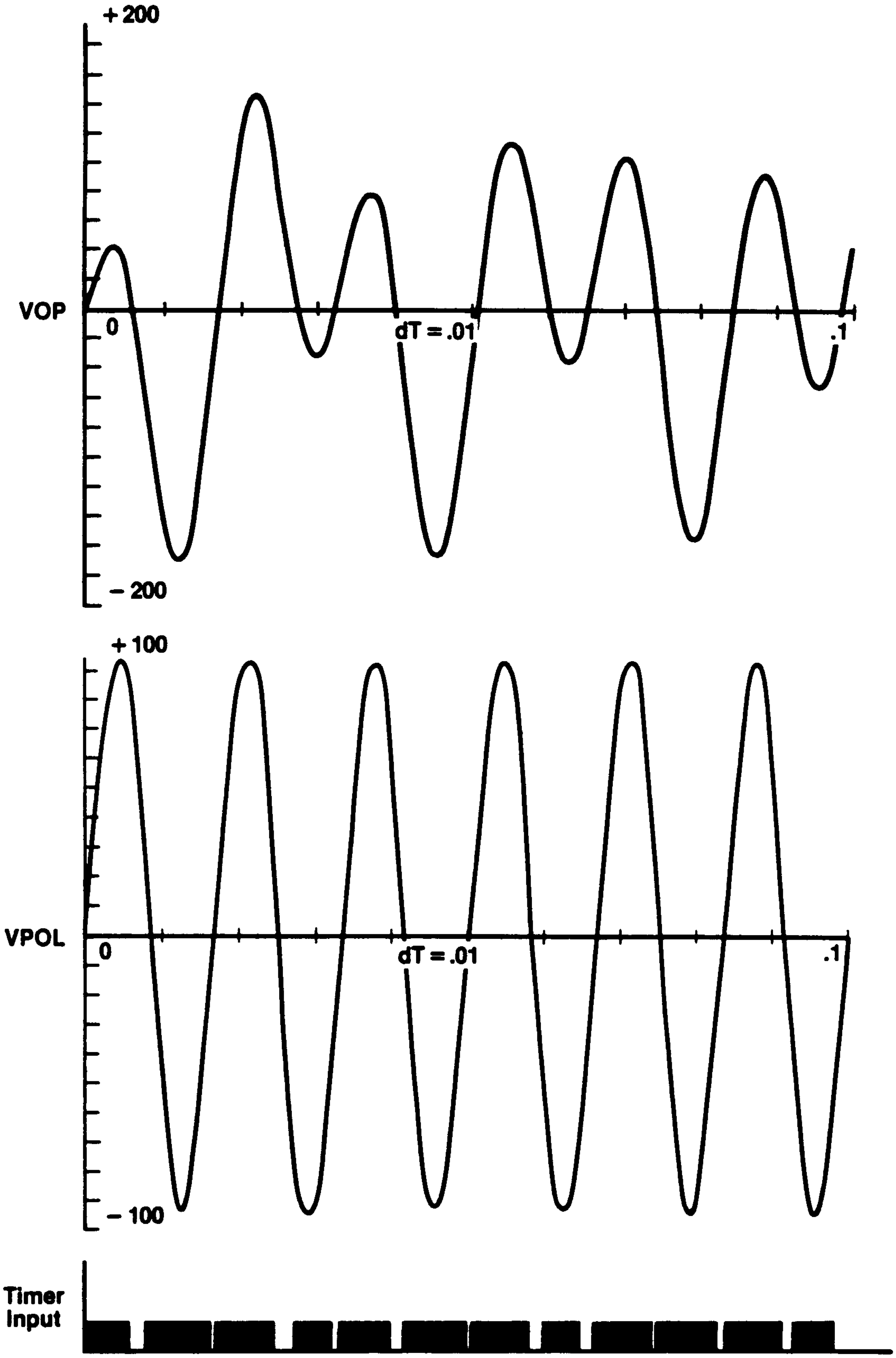
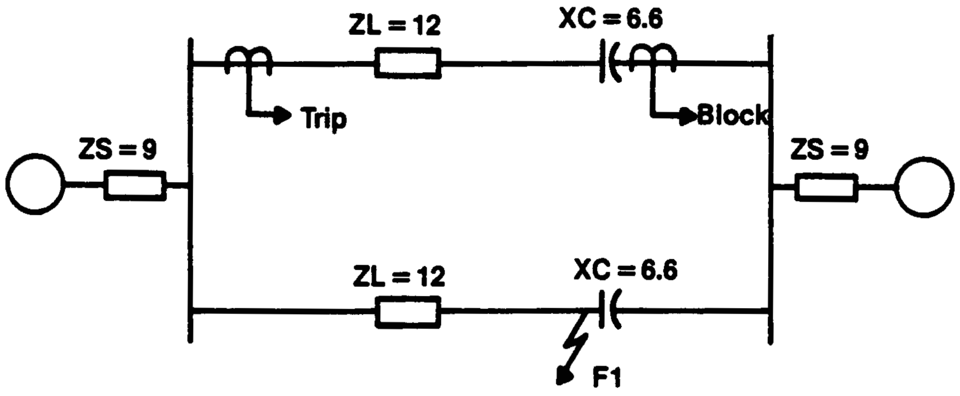


Figure 31



Typical System

Figure 32

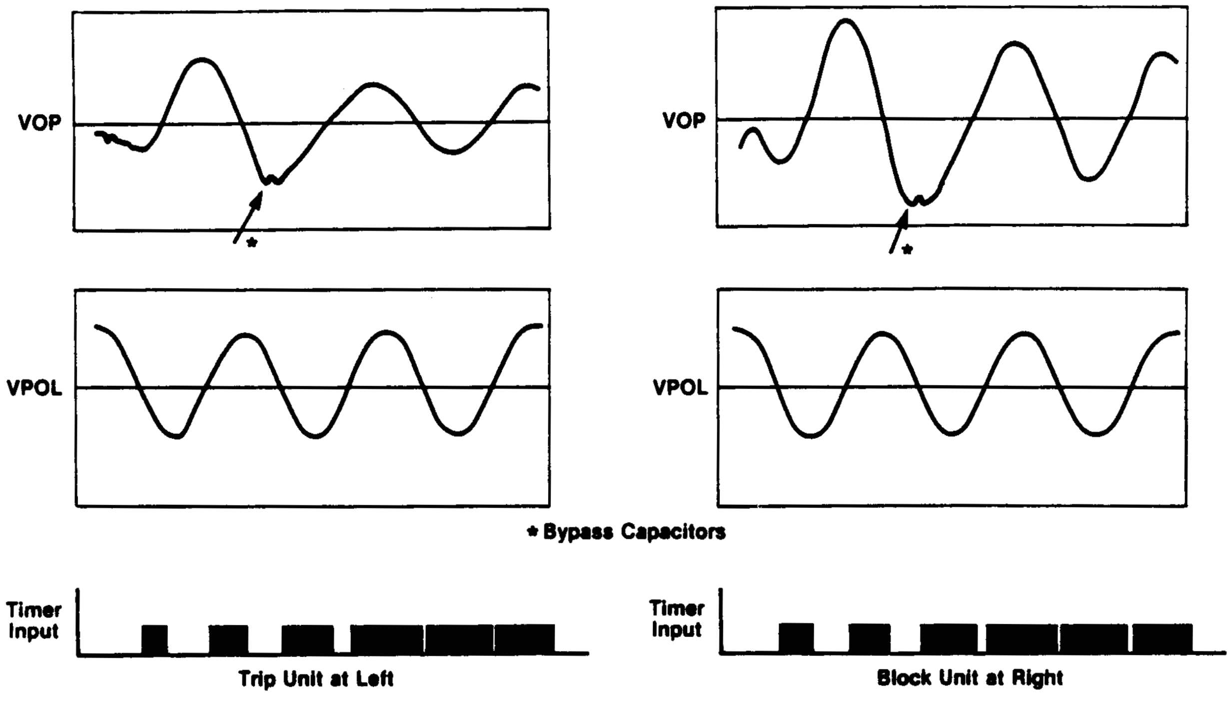
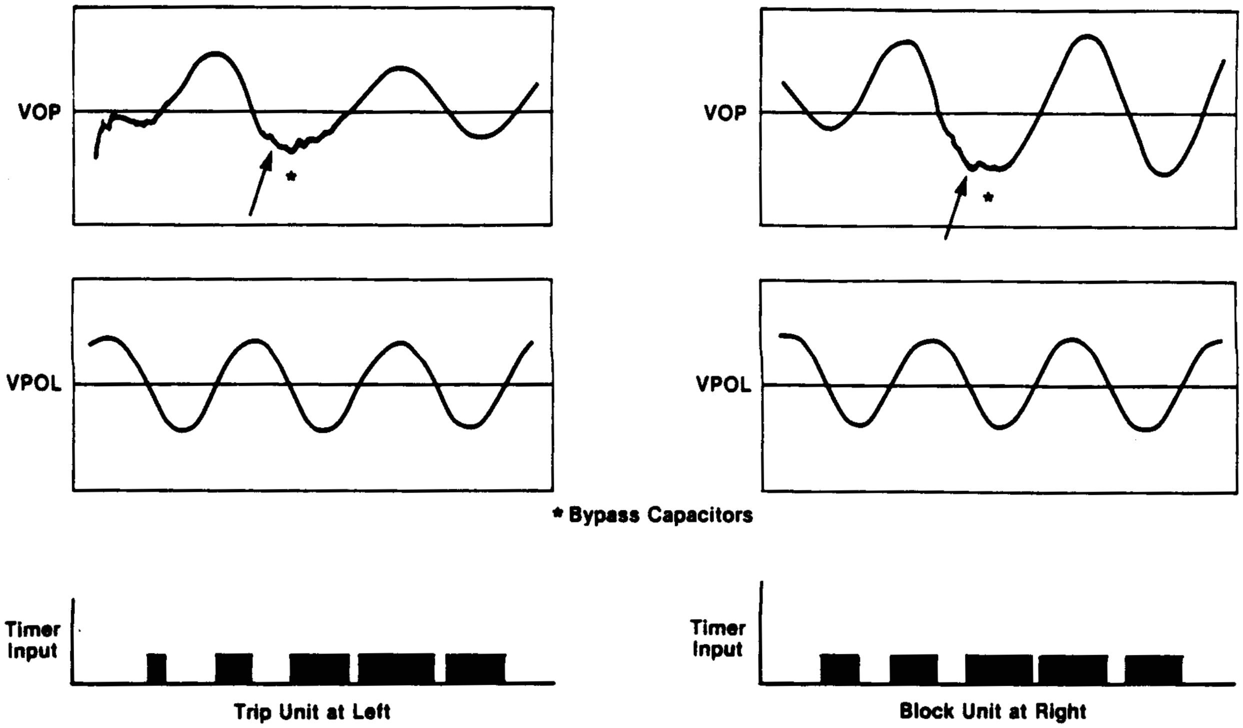
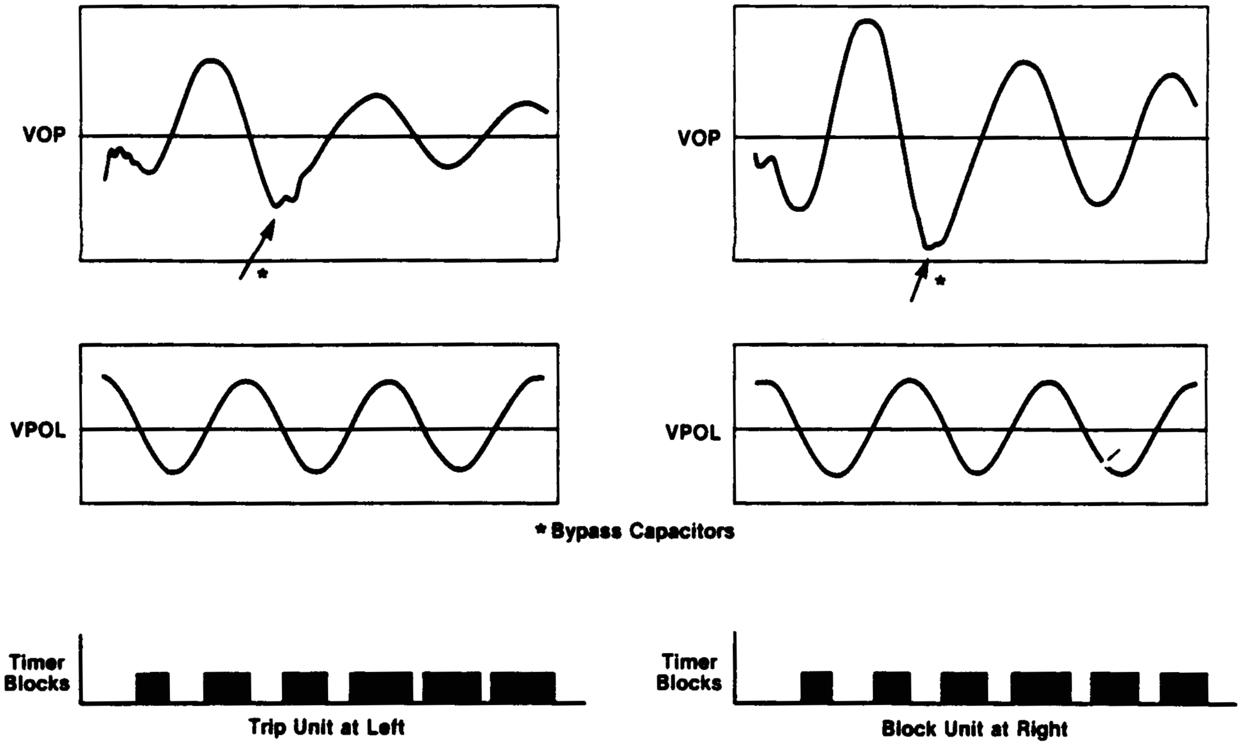


Figure 33



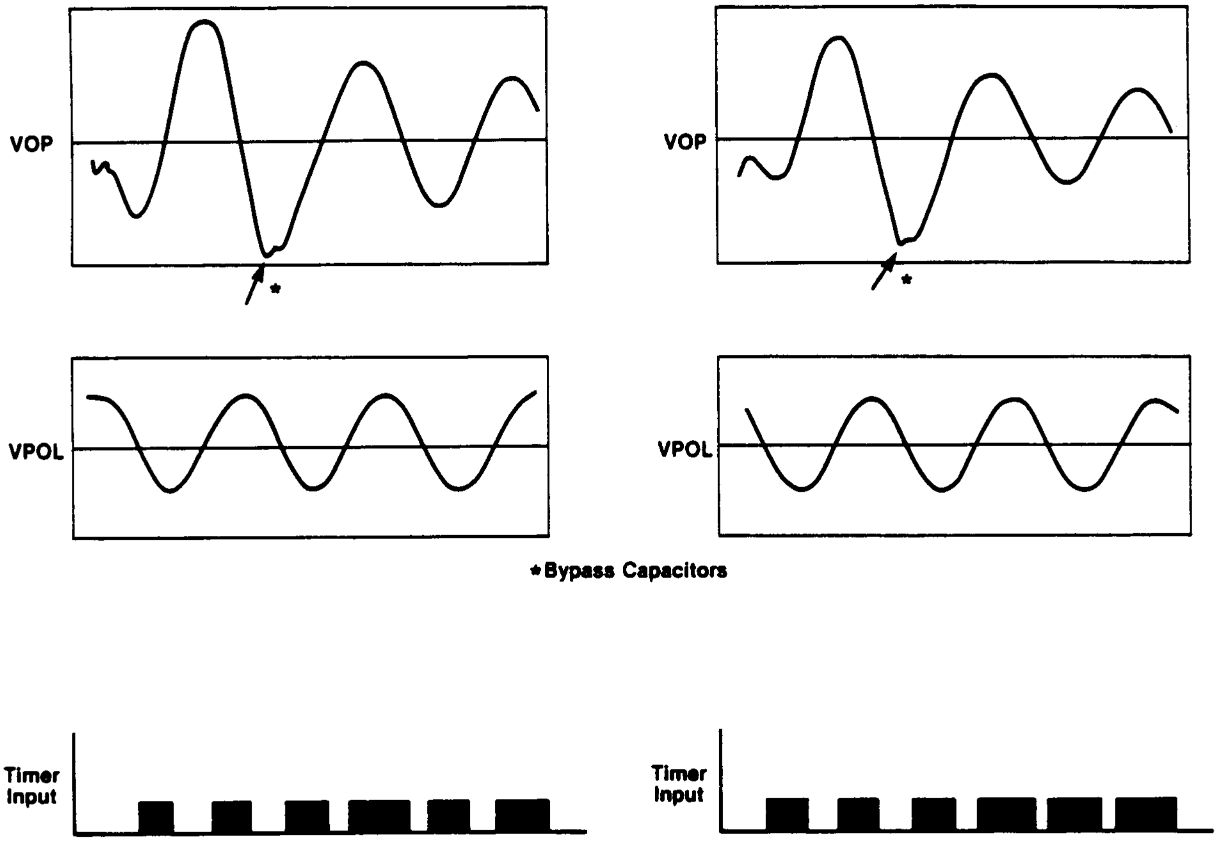
Right to Left Load Flow

Figure 34



Left to Right Load

Figure 35



*Bypass Capacitors

Blocking Unit Using Line Side Potential

Blocking Unit Using Bus Side Potential

Figure 36

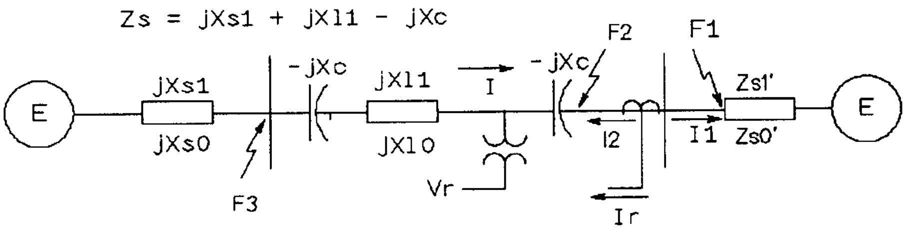
Series Compensated Line Protection: Practical Solutions

G.E. Alexander
J.G. Andrichak
W.Z. Tyska

A paper entitled "Series Compensated Line Protection: A practical Evaluation" (1) was presented to this conference in 1989. Problems associated with the protection of lines with series capacitors were discussed, but no specific solutions were given. Practical solutions to some of these problems are herein presented. The techniques discussed are used in various GE equipments (2)(3)(4)(5) which are applied at various locations throughout the world.

Dynamic Response

Distance functions are designed to perform correctly on a resistive/inductive system. When series capacitors are introduced to the power system, the normal voltage/current relationships can be affected when fault levels are not sufficient to produce flashing of the gaps or to produce significant conduction in the MOV's used to protect the capacitors.

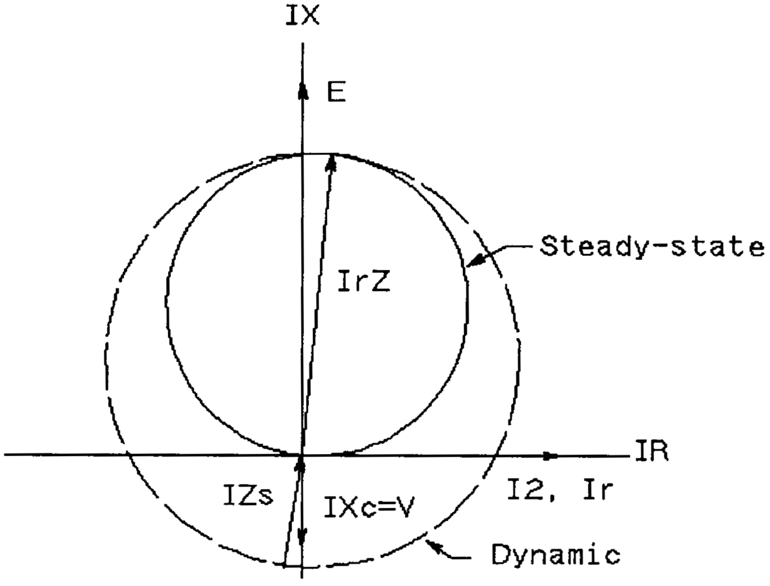


Simple System With Series Compensation

Figure 1

Consider the three-phase faults shown at F1 and F2 in Figure 1. The voltage at the right terminal of the line will be reversed from normal if gap flashing/MOV conduction does not occur, and distance functions located there will respond differently for each fault because F2 is an internal fault, whereas F1 is external to the line. Distance functions, when properly set, can be used under these circumstances, but the dynamic response must be relied on if correct performance is to be obtained.

The response of a distance function for the internal fault at F2 is shown in Figure 2. Note that the plot is made on and IR-IX basis which can be viewed as an equivalent R-X diagram if the current (I) is ignored. The diagram shows that a distance function looking in the forward direction (to the left in Figure 1) will operate correctly on a dynamic basis because the fault impedance, Xc, plots within the dynamic characteristic. But, it will not operate steady-state because Xc plots outside of (behind) the characteristic for this condition. Please note that the characteristic shown in Figure 2 applies for faults in the forward direction only. The function is directional; the area shown below the IR axis applies only for capacitive faults in the forward direction and NOT for faults behind it.



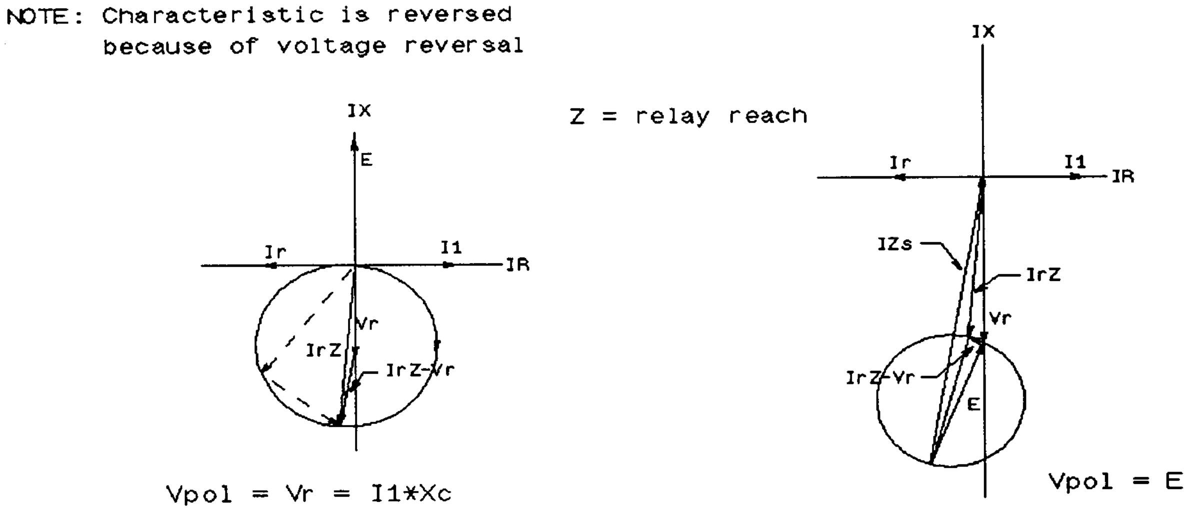
NOTE: area below IR axis applies for forward direction capacitive faults only, not for reverse faults.

Response of Mho Function for Fault at F2 in Figure
Figure 2

The characteristic of the same distance function for the external reverse direction fault at F1 is shown in Figure 3. Whether the function will operate on a steady-state or dynamic basis will depend on the reach of the function relative to the capacitive reactance, Xc.

a. If the reach is less than Xc, the function will operate dynamically (Figure 3b) but will not operate steady-state. This is of concern when trying to set a zone [function so that it will not overreach for a fault beyond a series capacitor at the remote end of the line (F3 in Figure 1). For example, consider a a zone 1 function that is applied at the right end of the line shown in Figure 1. If the reach setting required to prevent operation for faults at F3 must be made less than the reactance of the capacitor located behind it, then the function will operate dynamically for faults at F1. Thus, in these applications and for other reasons to be discussed below, it may not be possible to apply a simple zone 1 direct tripping distance function.

b. If the reach is greater than Xc, the function will operate steady-state (Figure 3a), but not dynamically. Since the overreaching functions m most pilot relaying schemes have a reach setting greater than Xc, they will not operate dynamically. In a properly designed relaying scheme, this will allow sufficient time to establish that the fault is external to the protected line and so prevent tripping in the event the fault hasn't been cleared before the overreaching functions operate steady-state. Such a scheme requires the use of blocking functions as shown in the simplified logic of Figure 4. The blocking functions are set to look away from the protected line, and will operate dynamically for external faults. The dropout time (B) of the characteristic timer for the blocking function is set relatively long to prevent the tripping function from initiating a trip before the external fault is cleared by the protective relays located on that line. Note that the tripping functions will operate dynamically for all internal faults (see Figure 2). They will operate faster than the blocking functions and will prevent them from operating by applying the NOT input to the AND shown in Figure 4.

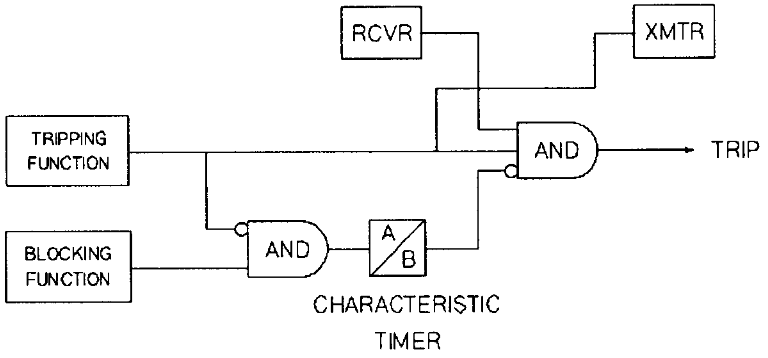


a. Steady-state Characteristic

b. Dynamic Characteristic

Response of Mho Distance Function for Three-phase Fault at F1 in Figure 1

Figure 3

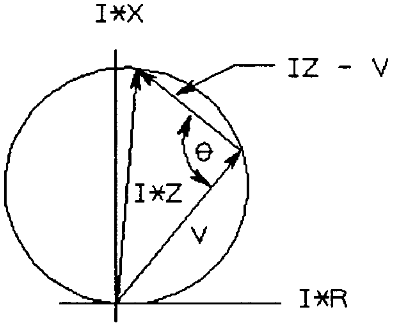


Simplified Scheme Logic

Figure 4

Zone 1 Direct Tripping Functions

A simple zone 1 function can be derived as shown in Figure 5. In this function, operation occurs whenever the angle between the operating quantity (I*Z - V) and the polarizing quantity V is less than 90 degrees.



Z = Relay Reach
I = relay current
V = relay voltage and polarizing quantity
I*Z - V = relay operating quantity

Simple Mho Distance Function

Figure 5

Consider that such a function is applied at the location illustrated in Figure 1. On the surface, it appears that the function could be set to reach 80-90 percent of the compensated impedance of the line (Xl1-Xc) to provide direct tripping. However, it was shown in the earlier paper that the function may overreach on the low frequency transients that could occur for faults beyond the capacitor when the fault level is insufficient to cause flashing of the gaps or to produce significant conduction in the MOV's used to protect the capacitors. It was also shown in that paper that it may not be possible to set this function with a short enough reach to prevent overreaching. Secondly, if a short enough reach could be found, it was just shown above that the function could operate for faults beyond capacitors located behind it. It was for this reason that a combined overcurrent/distance function was developed. In the simple distance function, the measurement is made by comparing the phase relationship of the operate signal (IZ-V) to the polarizing signal Vp; where Z is the reach of the function, and, V and I are the voltage and current at the function. In the combined distance/overcurrent function, the operate signal must also be larger than a user set magnitude in addition to having the correct relationship to the polarizing quantity. The level detector setting is determined by the amount of compensation and type of protection used around the compensation.

For example consider the fault at F3 in the system shown in Figure 1. For this fault, the voltage at the relay is:

$$Vr = Ir*(Xl1 - Xt)$$

Where,

Xt = Xc when gaps are used and are not flashed, or,
= zero when gaps are flashed

Xt = parallel combination of Xc and the MOV's when the latter are conducting, or, is equal to Xc when the MOV's are not conducting

If the zone 1 function is set with a reach, Z, equal to Xl1, then the operate signal (IrZ-Vr) for the fault at F is:

$$IrZ - Vr = Ir^*(Xl1) - Ir^*(Xl1-Xt) = Ir^*Xl1 - Ir^*Xl1 + Ir^*Xt$$
$$= Ir^*Xt$$

If gap flashing does not occur, of if there is not significant conduction in the MOV, then the operate signal, IrZ-Vr, is equal to Ir*Xc, the voltage across the capacitor. The level detector in the zone 1 function is set larger than this value so that it cannot operate for faults external to the zone of protection, even in the presence of low frequency transients.

If, for the fault at F3, the gaps flash or significant conduction occurs, then Ir*Xt is equal to zero if the gaps flash, or is less than or equal to the MOV protective level. Because this is less than the level detector setting, the function will not operate and is very secure for this condition. Similar reasoning can be applied to show that the function can be set properly so that it will not operate for reverse faults when capacitors are located between the function and the fault.

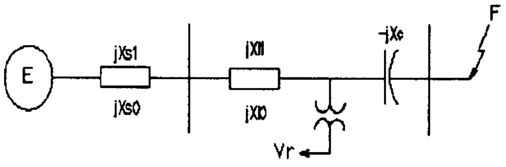
Now consider a fault directly in front of the function. For this fault (Vr = 0), and the operate signal IrZ-Vr = Ir*Z = Ir*Xl. If the source behind the function is very strong and/or the line is very long, the operate signal will be very large and fast operation wilt result. Both analog and EMTP model power system testing have demonstrated operating times in the 3-4 millisecond range for heavy close-in faults while maintaining a high degree of security for faults external to the line.

Polarizing Choice, Phase and Ground Distance Functions

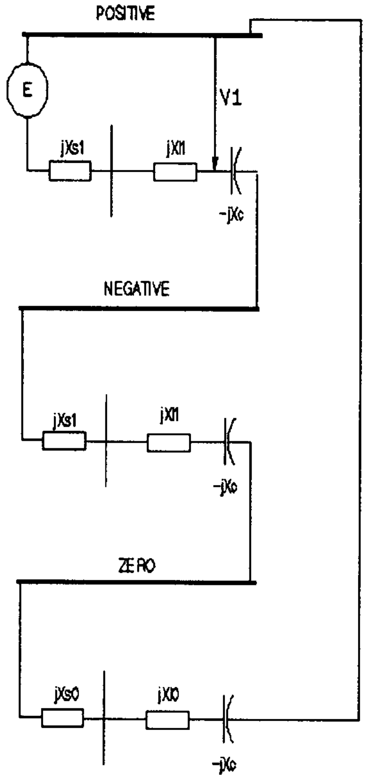
A number of choices are available in selecting the polarizing quantity to be used in phase and ground distance functions. The simple distance function described above uses the faulted phase/phase-pair voltage as the polarizing quantity. This choice has many drawbacks; including poor performance on series compensated lines, poor arc/fault resistance coverage, non-operation for zero voltage faults, and relatively poor performance in single-phase tripping schemes. Consequently, other quantities which provide better performance are commonly used. One choice is positive sequence voltage polarization which provides significant improvements in performance for the drawbacks just described.

When distance functions are applied near series capacitors, they can be made to operate properly on a dynamic basis, but, depending on the type of polarization, they may operate incorrectly on a steady-state basis as a result of the voltage reversals that can occur. Positive sequence voltage polarization will not prevent steady-state operation for three-phase faults, but will prevent it in many cases for unbalanced faults. For example, consider the simple system shown in Figure 6. In this system, the phase-to-ground voltage at a relay looking to the left will reverse for the phase-to-ground fault shown. The positive sequence voltage referenced to the faulted phase will not reverse however unless the capacitive reactance, Xc, exceeds the following value:

$$Xc > \frac{Xs1 + Xl1 + Xl0 + Xs0}{3}$$



a. Simple System with Series Compensation



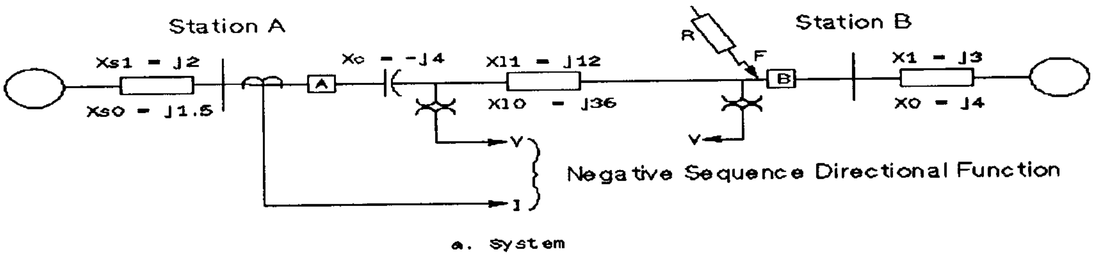
b. Network Connections for Phase-to-Ground Fault

Figure 6

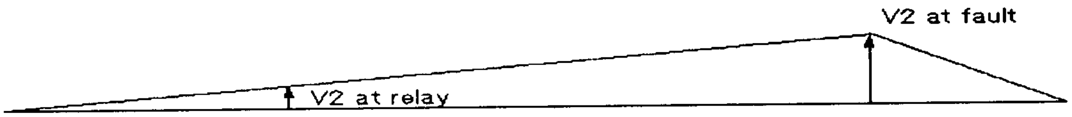
Similar analysis can be made for phase-to-phase and double-line to-ground faults to show that the functions will also perform properly on a steady-state basis for many of these faults.

Distance functions with positive sequence voltage polarization will provide continuous outputs for all but three-phase zero voltage faults because there will be some positive sequence voltage for all but three-phase faults. Dynamic performance is relied on for zero voltage three-phase faults.

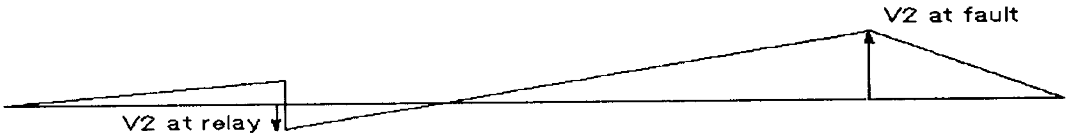
Positive sequence voltage polarization also provides increased security for faults behind the function and excellent performance in single-phase tripping schemes.



a. Typical System with Series Capacitors



b. Negative Sequence Voltage Profile (capacitor gaps flashed).



c. Negative Sequence Voltage Profile (capacitor gaps not flashed).

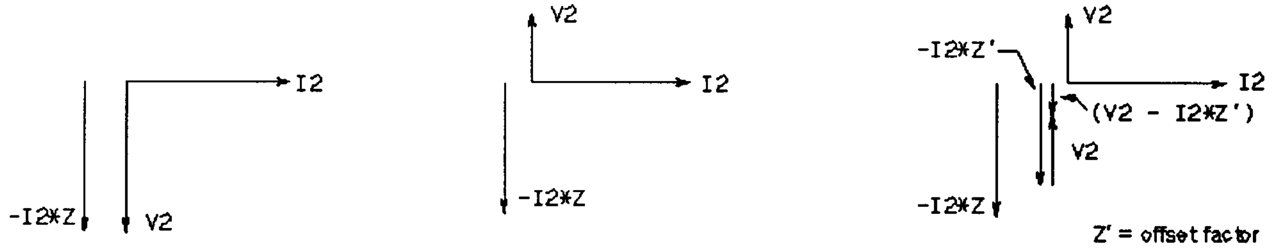
Figure 7

Directional Overcurrent Functions

Directional overcurrent functions can be used to provide excellent protection for high resistance ground faults but are susceptible to misoperation as a result of the voltage reversals that can occur for faults near series capacitors. In addition, zero sequence directional functions are also susceptible to the effects of mutual coupling from parallel lines.

Consider the system shown in Figure 7. For the fault shown, the negative sequence voltage at the relay will be reversed from normal when the fault current is not sufficient to cause flashing of the gaps or to produce significant conduction in the MOV's used to protect the capacitors. The zero sequence voltage can be similarly affected. If the reversed voltage is used in a directional function, the fault would appear to be external rather than internal to the line as shown in the Figure. Negative sequence directional functions are not affected to any extent by mutual coupling; and, they can be made secure from voltage reversals with the addition of an offset/compensating signal. Figure 8 shows in phasor form the performance of a simple negative sequence directional function versus the operation of a function with the offset/compensating feature. The performance of the functions are such that operation will occur whenever the I2*Z quantity is within 90 degrees of the V2 quantity in the simple function or within 90 degrees of the V2 - I2*Z' quantity in the compensated function. The offset/compensation factor must be set greater than the difference between the source impedance and the capacitive reactance shown in Figure 7; i.e., (Z' > Xs1- Xc).

NOTE: V2 and I2 phasors are for single-line-to-ground faults shown in Figure 7



a. Uncompensated Function
V2 vs -I2*Z
Capacitors bypassed

b. Uncompensated Function
V2 vs -I2*Z
Capacitors not bypassed

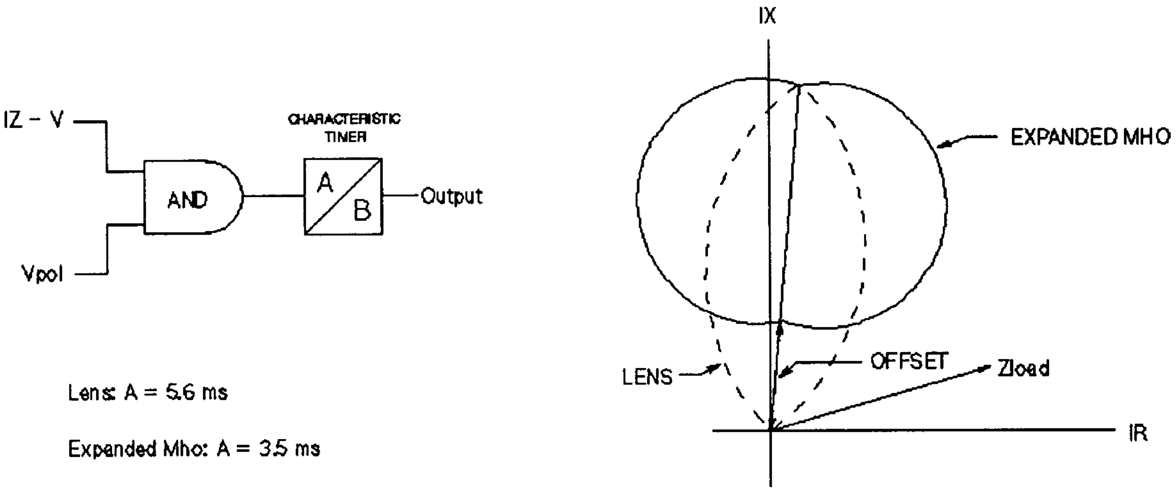
c. Compensated Function
(V2 - I2*Z') vs -I2*Z
Capacitors not bypassed

Performance of Negative Sequence Directional Functions on a Series Compensated Line
Figure 8

Forward Offset

A distance function can be made lenticular to minimize the effects of load, or forward offset can be used to achieve the same effect as shown in Figure 9. Furthermore, with the offset in, it is possible to use an expanded mho characteristic as opposed to a lenticular characteristic that would otherwise be required. This is also shown in Figure 9. Since the expanded mho characteristic is obtained by using a lower timer setting on the characteristic timer, the fastest possible operating time can be obtained for close-in heavy faults. Please note that the function will operate dynamically for forward faults in the offset area.

The offset will also be beneficial when the function is applied on some series compensated lines. For example, consider that a three-phase fault occurs at F1 in Figure 1. The apparent impedance, on a steady-state basis, will plot in the offset area (outside of the characteristic] if the offset is greater than the capacitive reactance of the capacitor (see Figure 10). Thus, the function will not operate steady-state, or dynamically as described earlier under dynamic response (Figure 3b). Since this is an external fault, this performance is desirable.

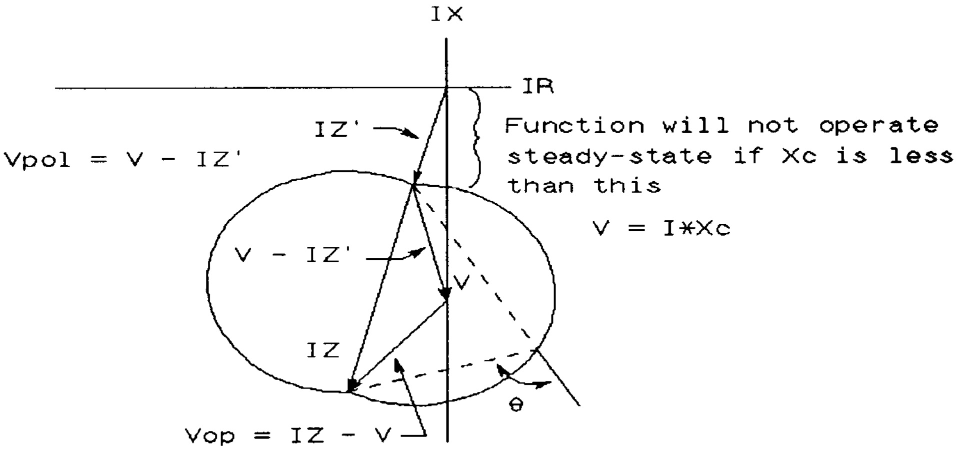


a. Simple Phase Angle Comparator

b. Characteristics

Expanded Mho with Offset versus Lens Characteristic

Figure 9



Function operates when angle between Vop and Vpol is less than θ degrees

Steady-state Characteristic of Offset Mho Distance Function
for three-phase Fault at F1 in Figure 1

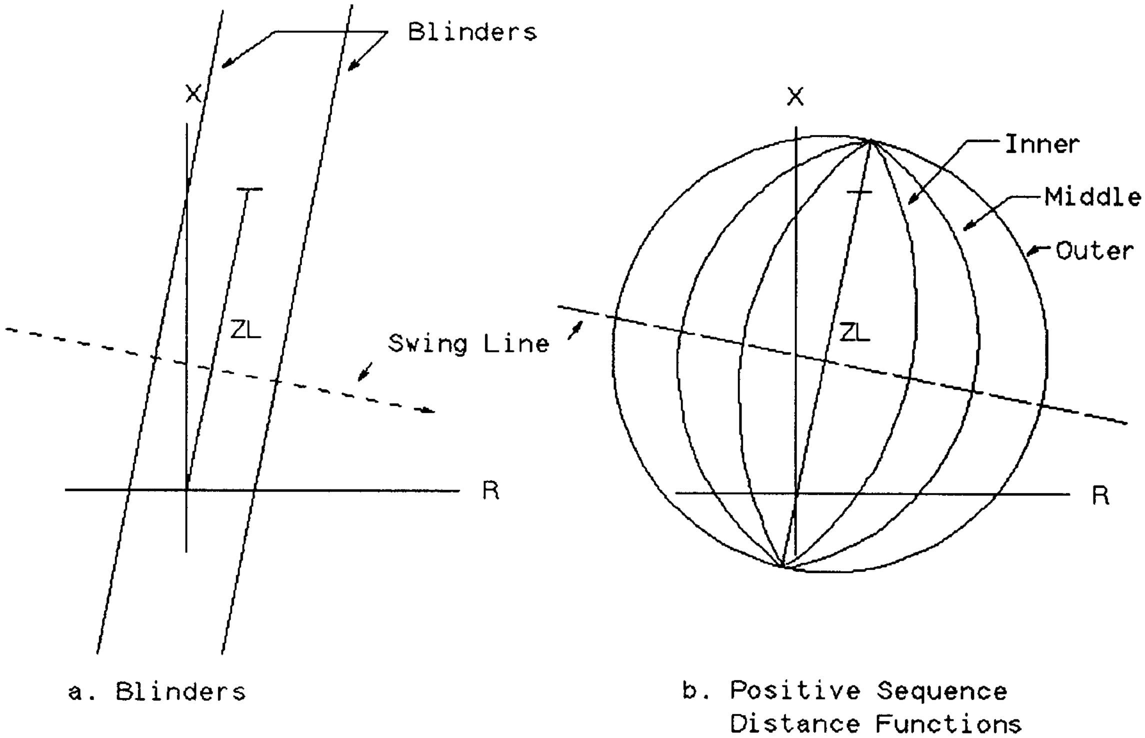
Figure 10

Asymmetrical Gap Flashing

Asymmetrical flashing of the gaps in one or two phase of the transmission line causes negative and zero sequence currents to flow in the transmission line. If either of these currents were used alone to operate an overcurrent function, then this function may operate when operation is not really called for. It is possible to minimize, and in some cases eliminate, the effects of the gap flashing by using overcurrent functions that have positive sequence current restraint. For example, a negative sequence current function would have as its operating quantity (I2 - K*I1) and a zero sequence current function would have as its operating quantity (I0 - K*I1). Either or both of these functions will still provide excellent coverage for high resistance ground faults, but with the security provided by the positive sequence current restraint.

Out-of-Step Tripping

Out-of-step tripping can be instituted in a number of ways. One method uses blinder functions as shown in Figure 11a. Positive sequence distance functions can also be used as shown in Figure 11b. Positive sequence distance functions have the following advantages over the blinder scheme.



a. Blinders

b. Positive Sequence Distance Functions

Out-of-Step Tripping
Figure 11

1. The positive sequence distance functions have a defined reach in both the forward and reverse directions, thus making them less susceptible to operation on swings external to the protected line.

2. The swing must cross both of the characteristics in the blinder scheme before a decision to trip can be made. The swing must pass through three characteristics (outer, middle, and inner) before a trip decision can be made. Tripping can be initiated once the inner characteristic is entered, or it can be delayed until the swing leaves the outer characteristic.

3. Gap flashing and capacitor reinsertion for some SLG faults near a series compensated line can cause the fault impedance to vary greatly. In fact, it may move in a manner similar to a swing condition which could cause undesirable operation of the out-of-step tripping system. Mho distance functions that measure positive sequence impedance are less susceptible to operation for this condition.

Conclusions

Series compensated lines offer unique problems to the protection engineer. These problems are not insurmountable and relays and schemes have been developed for use in the protection of these lines. The solutions to many of these problems have been presented herein. The techniques used to implement these solutions have been available for many years and have many years of experience on relaying schemes applied throughout the world.

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