IMPROVEMENTS IN
POLYPHASE LINE PROTECTION

by

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INTRODUCTION

The term "polyphase line protection" as used in the following discussion refers to a solid state line protection system in which the measuring units use sequence quantities. Such schemes are designated "polyphase" since generally each measuring unit can respond to faults of a given type (e.g., phase-to-ground) on all phases or phase-pairs, and some measuring units can respond to different types of faults.

Why use polyphase line protection? Consider two examples:

1. Zero sequence directional overcurrent relays are affected by zero sequence mutual coupling. Substitution of a negative sequence directional overcurrent relay is a common remedy on line sections where heavy zero sequence mutual coupling is present.

2. Distance relays of any design have an upper limit on ground fault impedance accommodation. Consequently, on any line where high impedance ground faults may occur (e.g., a tree touching a phase conductor) it may prove desirable to utilize a zero sequence or negative sequence directional overcurrent relay rather than a distance relay.

These are familiar examples that may not normally be associated with justifying the use of a polyphase line protection scheme since individual component relays can supplant or supplement conventional relays to take care of both situations. However, for a static relay system where the entire scheme is integrated into one or more 19 inch rack-mount boxes and all of the measuring units operate on sequence quantities, the two previous cases provide justification for use of such a polyphase scheme versus a more conventional scheme.[1]

PRIOR ART

Since 1970 GE has offered static directional comparison line protection schemes whose measuring units operate on sequence quantities. The basic measuring units are a negative sequence directional overcurrent unit and a positive sequence mho distance unit. These are employed in the simplest scheme designated SLYP/SLCN.[2] A negative sequence distance unit is added in the SLYP/SLYN scheme. This paper will describe the application considerations and design philosophy of a new modular relay system, designated PLS, that will replace the existing SLYP/SLYN and SLYP/SLCN systems.

The SLYP/SLYN scheme was developed first to fulfill the need for a directional comparison scheme that operated reliably on series compensated lines regardless of capacitor bank location or bypass gap flashing characteristics. The SLYP/SLCN scheme was subsequently introduced with somewhat simplified negative sequence measuring units. The SLYP/SLCN scheme has been widely applied throughout the world on series compensated lines, uncompensated lines adjacent to series compensated lines, and uncompensated lines not adjacent to series compensated lines. It is capable of single pole tripping with the addition of an optional phase selector unit.

The SLYP/SLYN and SLYP/SLCN schemes are offered as MODIII static relay equipments. In this configuration the measuring units are packaged in separate 19 inch rack-mount boxes which are mounted and wired on a rack or cabinet together with logic and output units. Such static relay equipments are only supplied as mounted and wired assemblies because of the need to control the wire routing which is an integral part of the equipments surge immunity. The new PLS polyphase line protection system will be offered as a modular system. This will greatly reduce the number of rack units of panel space required and will permit installation of the system as a component rather than a factory wired assembly.

The MODIII SLYP/SLYN and SLYP/SLCN schemes utilize the medium-scale integrated circuit design common to all MODIII equipment and the majority of their measuring units employ the standard MODIII phase angle comparator approach. The PLS scheme will utilize the new higher density modular logic circuitry which employs digital techniques for such things as timing. The analog PLS measuring units will employ a variation of an amplitude comparator termed an "energy comparator." The remainder of this paper will discuss the impact on the application and performance of the PLS scheme due to these new design concepts.

NEW DESIGN CONCEPTS

Traditionally most GE solid state directional and distance measuring units have employed phase angle comparator circuits. This has been the basic approach used in solid state distance relays from the early SLY/SLCG to the latest modular TLS relays. However, these units may also be implemented using an amplitude comparator as well as a phase angle comparator.

The use of amplitude comparators is not entirely new in GE designs. They have been used for many years in the SLYP/SLYN and SLYP/SLCN polyphase relay schemes. The operating principles of phase angle comparators and the existing amplitude comparators will be reviewed followed by an introduction to the new features of the "energy comparators" to be used in the PLS relay system.

Phase Angle Comparators -

A simplified block diagram of a phase angle comparator circuit used in GE phase distance relays is shown in Figure 1. In this circuit, the mho characteristic is developed by measuring the angle between the operating signal, V_{OP} = IZ-V, and the polarizing signal, V_{POL}. This measurement is accomplished by use of the coincidence logic circuit and the characteristic timer.

In the phase angle comparator, the minimum operating time is fixed by the characteristic timer which is typically set to produce a circular characteristic (i.e., 4.167 ms at 60 Hz -or- 5.0 ms at 50 Hz). For the simplest (i.e., theoretical) phase angle comparator, the operating time is a function of the phase angle between V_{OP} and V_{POL} and the fault incidence angle rather than the severity of the fault (i.e., the magnitude of the operating signal). Consider a fault just in front of the relay and a second fault at 90% of the relay reach as shown in Figures 2A and 2B respectively. Both faults produce the same steady state timer input blocks of one half cycle even though the operating signal for the close-in fault is much larger than that for the remote fault. Next consider a fault just beyond the reach of the relay as shown in Figure 2C. In this case the operating and polarizing signals are 180 degrees out of phase and therefore produce no input to the characteristic timer. Note, however, that the magnitude of the operating signal is very small. Any errors in the operating signal - such as those caused by CCVT errors - may cause the operating signal to reverse thus producing an undesirable operation of the measuring unit. In order to prevent such an overreach condition in a zone 1 relay, the operate signal must be filtered sufficiently to remove the erroneous signals or the reach must be reduced. Conventional GE phase and ground distance relays, that employ phase angle comparators, use sophisticated filtering techniques to reduce the effects of these non-fundamental input signals while minimizing the time delay associated with a filter circuit. These filtering techniques produce a measuring unit in which the operating time is a function of fault severity.

Amplitude Comparators -

As noted before, amplitude comparators have been used for a number of years in the SLYP/SLYN and SLYP/SLCN polyphase relay schemes. In these schemes the amplitude comparators are used in the negative sequence distance unit and restrained overcurrent units.

A block diagram of the negative sequence distance unit used in the SLYN relay is shown in Figure 3. In this design, the minimum operating time is again determined by the setting of the characteristic timer - typically 90° - as it is in the phase angle comparator design. Figure 4 shows the operate and restraint signals and the characteristic timer inputs for two fault conditions. The magnitude of the signals is the same in each case; however, in Figure 4A the signals are in phase while in Figure 4B the signals are 90° out of phase. Note that for the same magnitude of input signal, the timer input can vary from a 90° block to a 180° block. Even though this function operates on a comparison of signal magnitudes, the speed of operation is not directly related to the fault severity. In this regard the circuit is similar to the simple phase angle comparator implementation.

Energy Comparator -

The amplitude comparator circuits used in the new modular PLS relay system are similar to those used in the SLYP/SLYN and SLYP/SLCN relays except for one major improvement: the 90° characteristic timer has been replaced with an integrator circuit and a level detector circuit as shown in Figure 5. In this circuit, the signals are linear up to the level detector stage. Therefore the output of the integrator stage varies as a function of the difference between the operate and restraint signals. This provides an operating time based on fault severity. A close-in fault as compared to a remote end fault produces a larger signal to drive the integrator output more quickly to the trip level. Initially, in the quiescent state the integrator is driven into a restraint condition by a switched bias which provides secure operation for all faults. This bias is switched out on the occurrence of a fault by a sensitive, high-speed fault detector (FD). The fault detector operates on negative and zero sequence currents or on a sudden change of positive sequence current.

The integrator stage does not consist of a pure integrator (i.e., a capacitor), but rather a parallel resistor-capacitor circuit as shown in Figure 6. The RC time constant provides filtering of the signals and establishes the operating time of the unit. The smoothing effects of the integrator cause the fault incidence angle and the phase angle between the operate and restraint signals to have only a secondary effect on the operating time. Typical waveforms for the unit are shown in Figure 7.

The amplitude comparator plus integrator is termed an "energy comparator." This approach is used in the positive sequence distance units, negative sequence distance and directional units, and the overcurrent units of the PLS system.

Positive Sequence Distance Unit -

As in the SLYP/SLYN and SLYP/SLCN schemes the PLS incorporates a positive sequence distance unit whose main purpose is to detect three phase faults. The PLS positive sequence distance unit utilizes an energy comparator with unique inputs, and its operation is somewhat like a voltage restrained directional relay. Figure 8 shows a simplified diagram of this PLS unit. By taking the positive coincidence of V_{POL} and I_1Z_R as an operating signal, the negative coincidence of V_{POL} and I_1Z_R as one restraint, and V_1 as a second restraint, mho and lenticular characteristics can be obtained as in a conventional distance relay using a phase angle comparator.

Figure 9 illustrates the balance point conditions that produce a circular or mho characteristic. A different shape characteristic is obtained by changing the effective magnitude of the restraint energy (negative coincidence) compared to the operating energy (positive coincidence). To obtain a more lenticular characteristic the weighting of the energy out of the negative coincidence circuit is increased relative to that out of the positive coincidence circuit. However, this does not significantly change the performance of the unit on internal faults since I_1Z_R and V_{POL} will be almost in phase and the output of the negative coincidence circuit will approach zero. This is advantageous since the operating time will not increase significantly when the characteristic is changed from a circle to a lens as is the case when a phase angle comparator is used.

Logic Circuit Techniques -

The PLS is not a digital relay in the sense that it does not operate on discrete current and voltage samples. This is obvious from the prior description of the analog "energy comparator" measuring unit design. A microprocessor is not used to implement the logic or timing functions, but much of the scheme logic will be implemented using Application Specific Integrated Circuits. The term Application Specific Integrated Circuit (ASIC) encompasses a family of devices that includes Programmable Logic Devices (PLDs). A PLD is a prefabricated integrated circuit that contains a collection of logic gates that the IC manufacturer produces in a generic configuration. The user then programs the device to create a specific application. A typical PLD is a Programmable Logic Array device, better known as a PLA, and this is the type of Application Specific Integrated Circuit that is used in the PLS.

ADVANTAGES OF ENERGY COMPARATOR FOR DISTANCE/DIRECTIONAL UNITS

The energy comparator approach for distance units has a number of advantages over the traditional phase angle comparator approach. A main advantage of the energy comparator is the speed of operation for close-in severe faults. With phase angle comparators and energy comparators the speed of the relay system is primarily predicated on the need to prevent false tripping due to the transient overreach attributable to CCVT transient errors. One solution with phase angle comparators is to provide a fixed time delay that will override the maximum period that the CCVT transient can appear as a net operating signal. Other phase angle comparators use a filter delay plus a fixed operating time imposed by the characteristic timer. The energy comparator virtually eliminates the fixed operating time associated with a characteristic timer, permitting operating times in the order of 2-3 ms for close-in severe faults that will be most critical to system stability.

The operating time of the energy comparator can be estimated by:

$$t = T_{RC} \ln \{(|V_R|+|V_{OP}|)/\ |V_{OP}|\}$$

where:

V_R = the prefault restraint voltage

V_{OP} = the magnitude of $(I_{fault}Z_{relay} - V)$

T_{RC} = the time constant of the integrator

ln = natural log

For example, in a distance unit where the restraint is limited to 0.5 pu, T_{RC} is 10 ms, and the value of IZ-V is 1.5 pu, the operating time will be approximately 2.9 ms. The calculation assumes an average value of IZ-V. There will be a minor variation in operating time based on fault incidence angle, and there is a small filter delay in a low-pass filter ahead of the distance unit.

The primary advantage of the energy comparator is the facility with which a distance (or directional) unit can be modified to enhance the overall performance of the relay scheme. One example is the simple addition of an I_0Z_{R1} restraint signal to the positive sequence distance unit in a single pole tripping and reclosing scheme. The I_0Z_{R1} restraint blocks the positive sequence distance unit from operating on single line to ground faults thus permitting the unit to initiate a three pole trip directly on interphase faults. Another example is the addition of restraining signals to the out-of-step blocking unit to ensure coordination of the out-of-step blocking unit and the tripping units on internal faults. The added signals are I_2, I_0, and D(IZ-V) which prevent or substantially delay the operation of the out-of-step blocking unit on internal faults. This permits a greatly simplified application of out-of-step blocking compared to more conventional designs. D(IZ-V) indicates "delta IZ-V" which is the difference in the (IZ-V) quantity between the fault and pre-fault value - in effect the fault component of the (IZ-V) quantity.

A further example is the use of the operating energy in the negative sequence tripping directional unit to restrain the negative sequence blocking directional unit. This permits the blocking unit to employ a hybrid design (i.e., a combined directional/ overvoltage unit) that provides very reliable operation on external faults thereby enhancing the coordination between the local blocking and the remote tripping directional units.

Another feature of the energy comparator is the use of non linear circuits in the operate signal path to increase the weighting of the operate signal during an internal fault. This feature is used in certain measuring units, such as the negative sequence distance unit, where the operate signal for an internal fault exceeds the operate signal for an external fault. The result is faster operation on internal faults.

POLYPHASE LINE PROTECTION SCHEME IMPROVEMENTS

Enhancements -

The PLS line protection system offers the following enhancements compared to the SLYP/SLCN scheme:

1) increased security

2) increased sensitivity to high resistance ground faults

3) ability to set the positive sequence distance unit to prevent operation on load flow (up to a maximum value) without increasing the operating time

4) improved phase selectors for single pole trip and reclose schemes

Increased security is achieved by reducing the number of external faults that are detected by the tripping units since, quite simply, the probability of a false trip increases in direct proportion to the number of external faults detected by the tripping units. The SLYP/SLCN scheme overcurrent trip unit is primarily responsive to the level of negative sequence current, but has a restraint proportional to positive sequence current (i.e., I_2-KI_1). The PLS overcurrent trip unit, IT, adds a zero sequence operate quantity to the negative sequence operate quantity which results in I_2 having less of an affect. Advantage is taken of the fact that the zero sequence current is typically much smaller than the positive and negative sequence currents for external faults. Given the same system, the PLS IT unit will operate for fewer external faults than will the corresponding unit in the SLYP/SLCN scheme.

The use of an energy comparator for the PLS IT unit also adds to the security as compared to the SLYP/SLCN scheme. The energy comparator will result in comparatively longer operating times on remote external faults. This increases the probability that the external fault will be cleared before the PLS can operate thus diminishing the possibility of a misoperation where a false channel operation might occur during the fault.

Increased sensitivity to high resistance ground faults is achieved by utilizing "adaptive" restraint in the overcurrent tripping unit, IT. In the SLYP/SLCN scheme the overcurrent trip unit setting must be increased by the maximum negative sequence shunt current (based on maximum negative sequence voltage, V_2, on the line). This is required to prevent a misoperation with a tripping scheme and to assure coordination with the remote overcurrent blocking unit in a blocking scheme. However, during a high resistance ground fault V_2 will be substantially less than its worst case maximum value. With this approach, the higher setting on I_2-KI_1 due to the fact that the worst case must be considered limits the sensitivity to ground fault resistance.

The new approach used in the PLS is to derive an IT restraint signal proportional to the negative sequence voltage. Therefore as V_2 increases the IT unit restraint is increased whereas for little or no V_2 the IT unit is close to or at its most sensitive pickup value. This "adaptive" restraint for the shunt charging current results in the PLS having a greater sensitivity to high resistance ground faults as compared to the SLYP/SLCN scheme.

The steady state coverage on the R-X diagram of the positive sequence distance unit must be restricted to prevent operation of the unit for maximum load flow. In the SLYP/SLYN and SLYP/SLCN schemes the characteristic timer setting, associated with the phase angle comparator, is increased to produce a lens characteristic which moves the characteristic away from the maximum load impedance point as illustrated in Figure 10. The penalty incurred is an increase in the units operating time. As discussed previously, the PLS positive sequence distance unit employs an energy comparator, and the way in which the characteristic is made lenticular results in little or no increase in operating time. However, for very heavy load flow it may be necessary to increase the time constant of the associated integrator which will produce an increase in operating time.

A significant improvement in the PLS relay system is the new design for the phase selector units which are required for single pole trip and reclose schemes. A new approach was selected for the phase selector in order to achieve three important goals:

1) Eliminate the need for settings

2) Operate on current only for easier application on series compensated lines

3) Provide correct phase selection for all unbalanced faults

The design selected to meet these goals utilizes an energy comparator similar to those used in the other measuring units of the scheme. The operate signal of the phase A unit consists of the phasor sum of $D(I_A)$, $2I_{A2}$, and I_0. As explained previously, $D(I_A)$ indicates "delta I_A" which is effectively the fault component of I_A. The restraint signal is the phasor sum of $D(I_B)$, $D(I_C)$, and $2I_{A2}$. The individual components of the operate signal were selected so that they tend to add in phase, or nearly in phase, in the faulted phase(s). The individual components of the restraint signal were selected so that they tend to cancel each other in the faulted phase(s). For single line to ground faults, the restraint signals in the faulted phase tend to cancel only on remote end faults where the ratio of zero sequence to negative sequence current can be quite low. In the unfaulted phases, the restraint signals tend not to cancel providing improved discrimination between the faulted and unfaulted phases. In the case of phase to phase faults, the unfaulted phase selector has an operate signal equal to the restraint signal. To ensure restraint in this case, a portion of the net operate signal in one phase selector is introduced as a restraint signal into the other two phase selectors.

It is apparent that the addition of phase quantities and sequence quantities would be greatly affected by load current. To circumvent this problem, the change in the phase current - in effect the fault component of phase current - [$D(I_A)$, $D(I_B)$, $D(I_C)$] is used instead of the total phase current. This method of obtaining the fault component of phase current results in only transient operation for phase to phase faults. To provide a steady state output, the scheme logic is arranged such that three pole tripping is initiated in the absence of any phase selector output if the negative sequence distance relay operates. For the same reason, operation of the positive sequence distance relay results in three pole tripping. However, the selection of input signals to the phase selector comparator was influenced by the desirability of maintaining a steady state output on single line to ground faults which, in the case of very high resistance faults, may be slower in clearing.

An initial restraint level is established in the energy comparator when the fault detector is not operated. Operation of the fault detector (FD) removes the restraint input which results in the restraint decaying with the integrator time constant.

Application Simplification -

A major design goal for the new PLS relay system was to simplify the application compared to the SLYP/SLCN scheme. This has been achieved as evidenced by the following examples:

1) Eliminating the need for a setting on the overcurrent blocking unit

2) Virtually eliminating settings for the out-of-step blocking function

3) For standard applications, the ability to set most of the measuring units using line impedance data only

4) Eliminating the need for phase selector settings

In the SLYP/SLCN scheme the overcurrent blocking function, $I_2(B)$, must be set above the maximum negative sequence current in the protected line for normal load conditions. This requires a knowledge of the negative sequence unbalance due to untransposed lines and/or maximum load unbalances. This value is not always easy to obtain. The PLS overcurrent blocking function, IB, utilizes a portion of the positive sequence current as a restraint signal. This positive sequence current restraint prevents IB from operating on negative sequence current present during normal load conditions and relieves the user from determining a setting.

In a previous section of this paper it was pointed out that the PLS out-of-step blocking unit, POSB, utilized additional restraint signals to prevent or substantially delay its operation on internal faults. This simplifies the application since the timer in the out-of-step blocking logic, which is traditionally the only setting that discriminates between a swing and a fault, may now be set without a rigorous determination of the impedance-time characteristic of the swing locus while assuring that the fastest swing will be detected.

Except for series compensated line applications, most PLS measuring unit settings can be determined knowing only the impedance of the protected line section. Absolute values of equivalent source impedance or source/line impedance ratios are generally not required. Only the positive sequence distance unit setting requires a knowledge of maximum load flow on the line.

In the previous section of this paper that described the PLS phase selectors it was pointed out that settings are not required. For single pole trip and reclose schemes this is perhaps the most significant simplification for the PLS versus the SLYP/SLCN scheme.

CONCLUSION

A new PLS relay system has been developed which will replace existing SLYP/SLYN and/or SLYP/SLCN polyphase line protection schemes. New design concepts, primarily the use of "energy comparator" analog measuring units, will result in the PLS having better performance than the SLYP/SLCN scheme and being easier to apply than both the SLYP/SLYN and SLYP/SLCN schemes.

REFERENCES

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2. Type SLYP-SLCN Static Directional Comparison Relaying Description and Application, General Electric Publication GET-6456A.

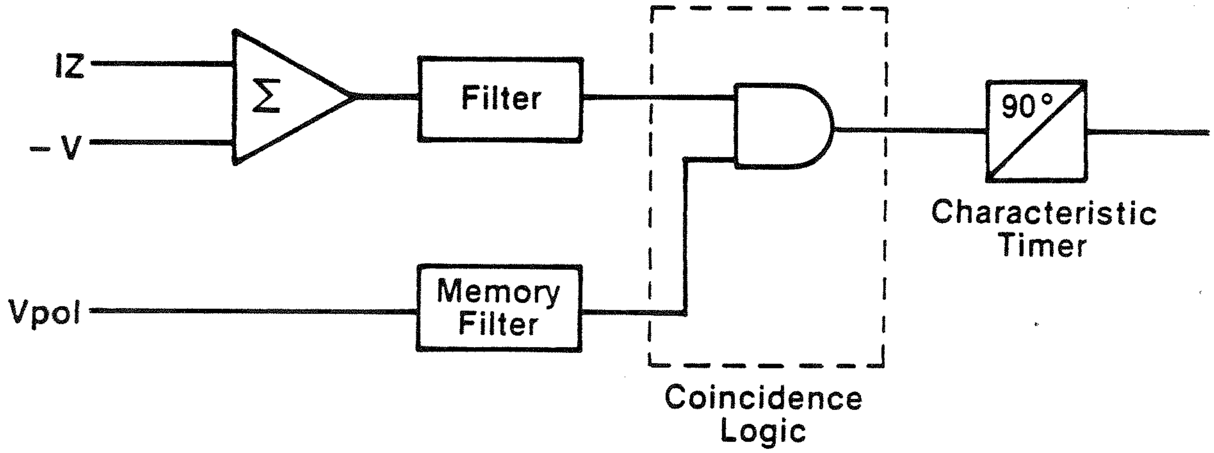
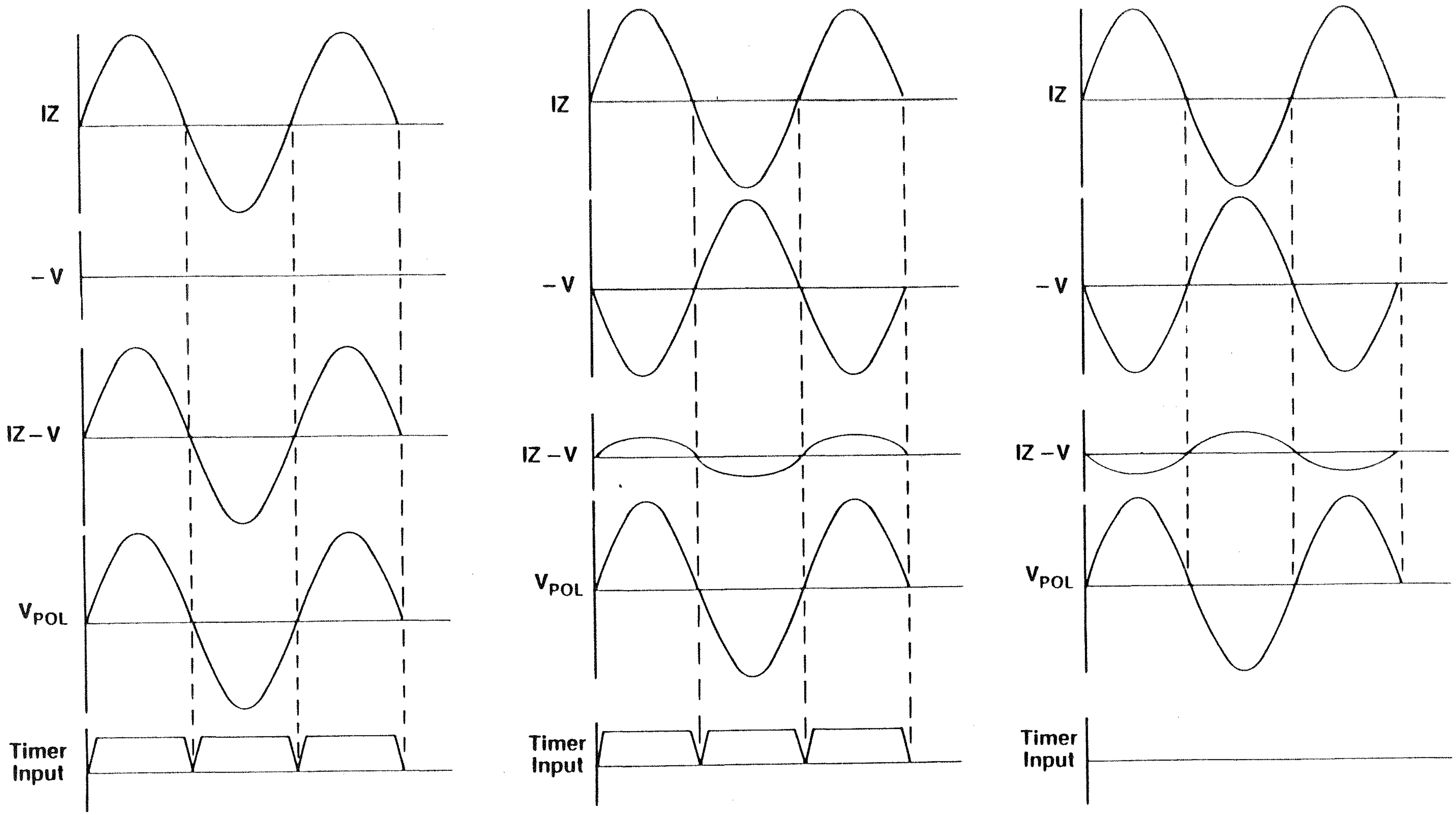


Figure 1.
Typical Phase Angle Comparator

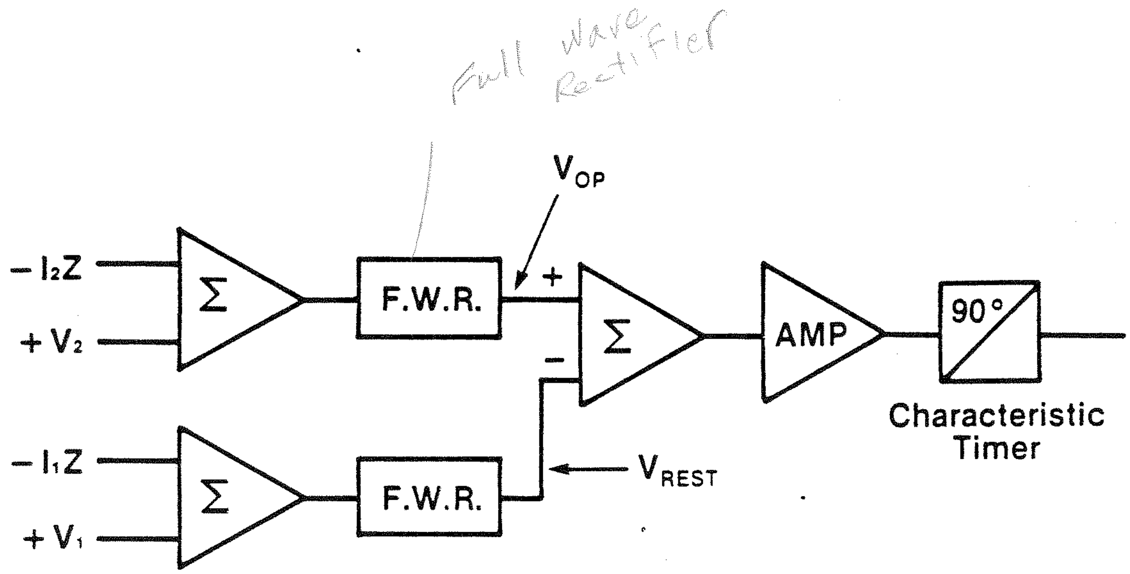


(A) Internal Fault at Relay Location

(B) Internal Fault Near Balance Point

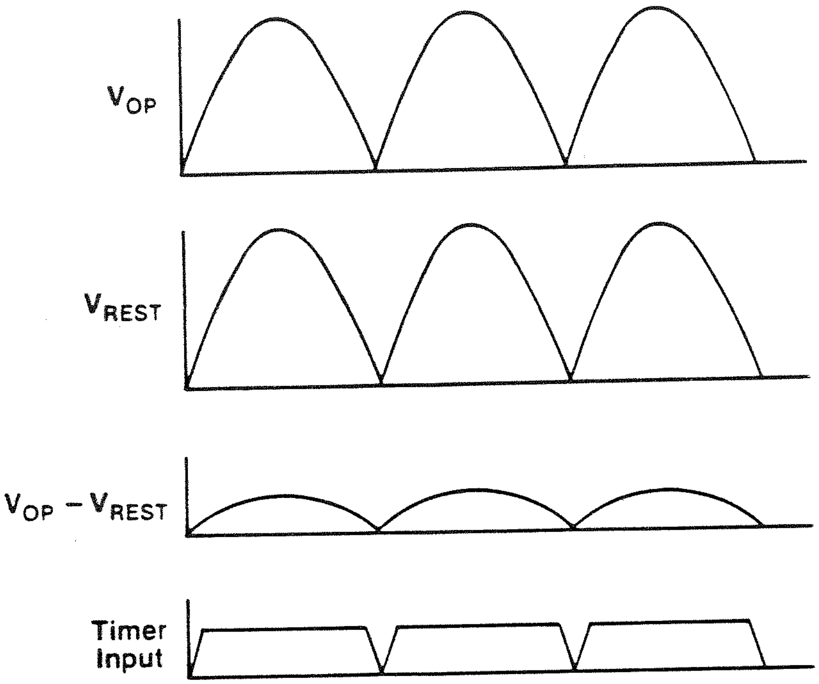
(C) External Fault Just Beyond Balance Point

Figure 2.
Phase Angle Comparator Waveforms

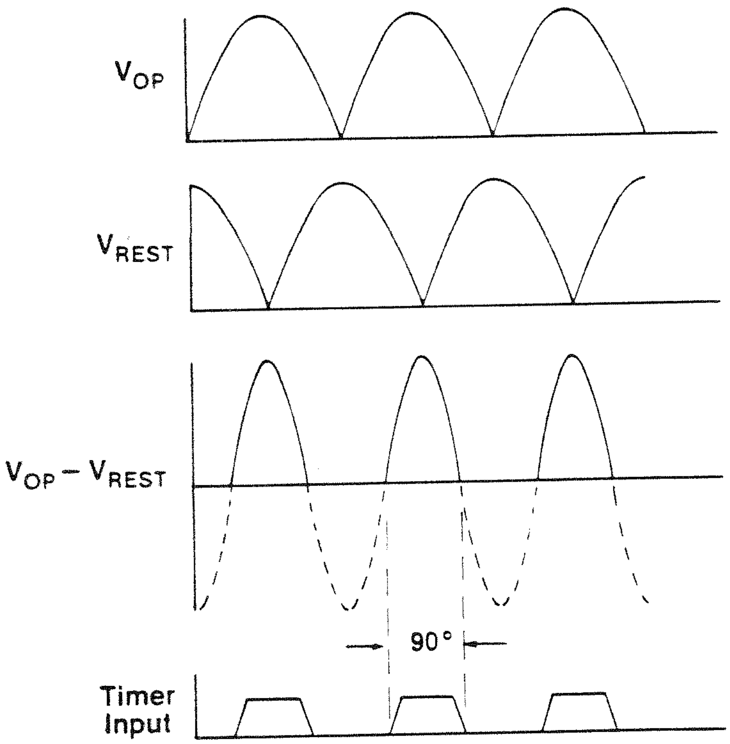


F.W.R. ⟶ Full Wave Rectifier

Figure 3.
SLYN Negative Sequence Distance Unit
Using an Amplitude Comparator



(A) V_{OP} and V_{REST} in Phase



(B) V_{OP} and V_{REST} 90° out of Phase

Figure 4
Amplitude Comparator Waveforms

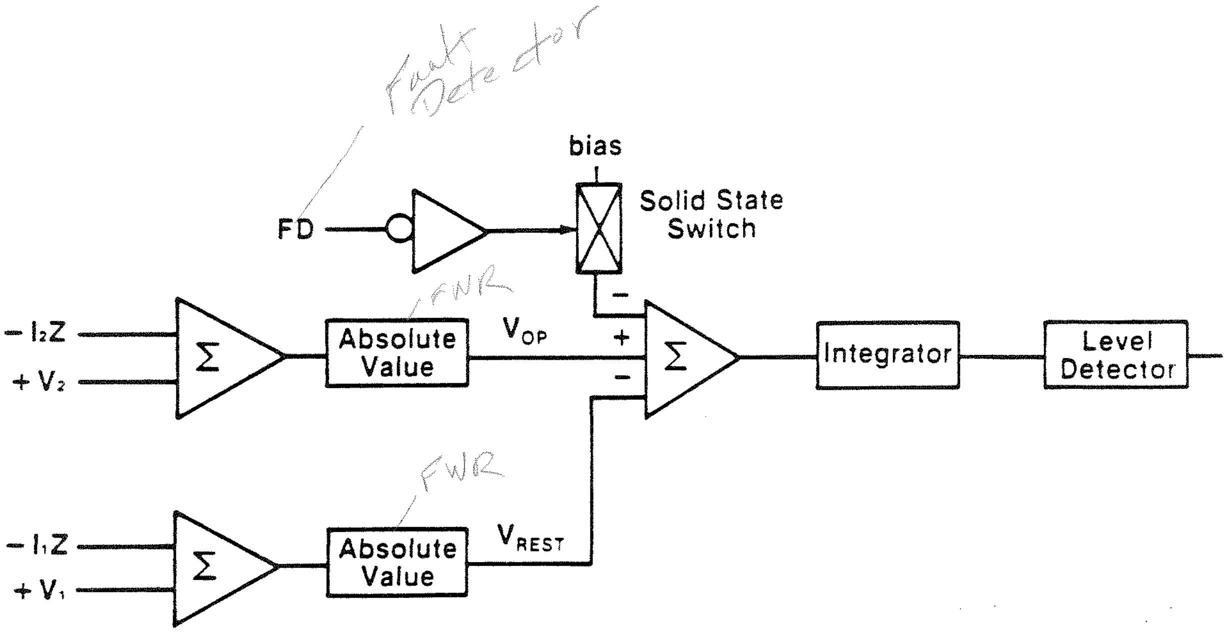


Figure 5.
PLS – Negative Sequence Distance Unit
Using Amplitude Comparator with Integrator

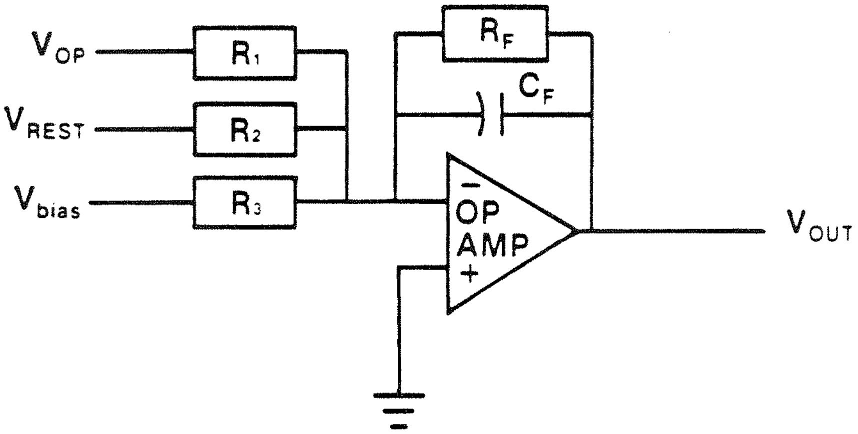


Figure 6.
Typical Integrator Stage

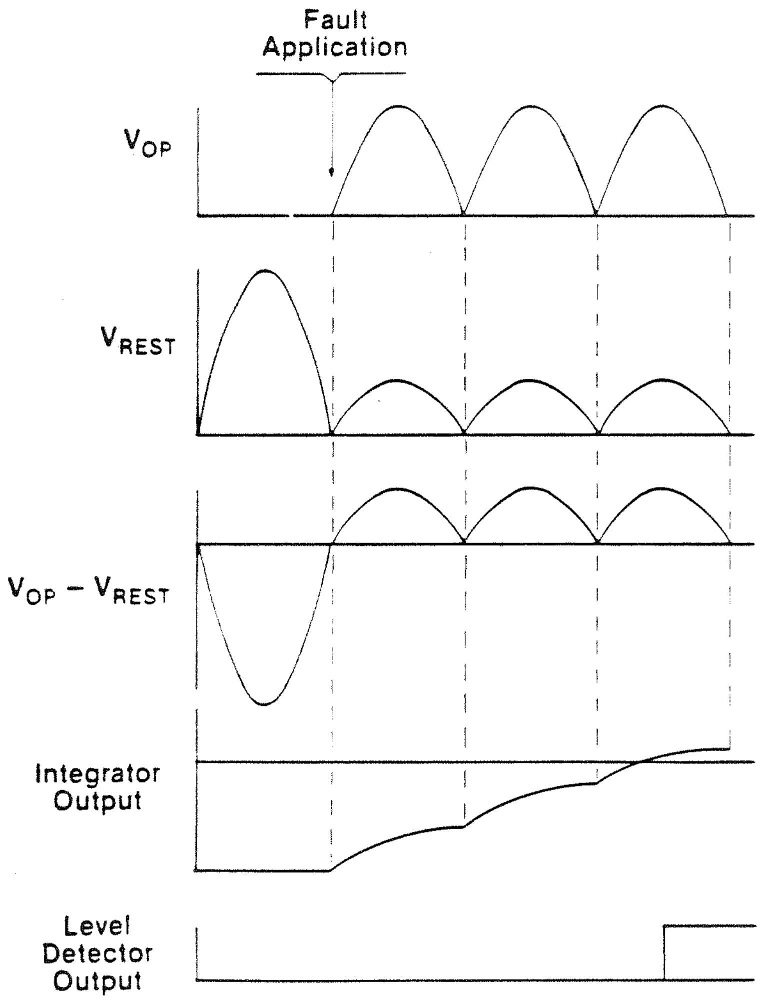


Figure 7.
Typical Waveforms for Energy Comparator

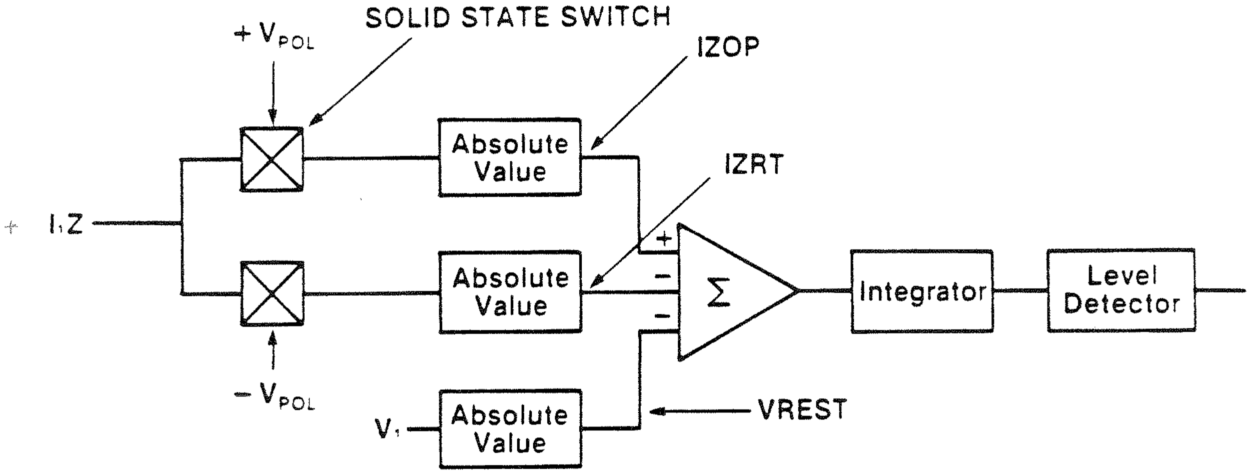
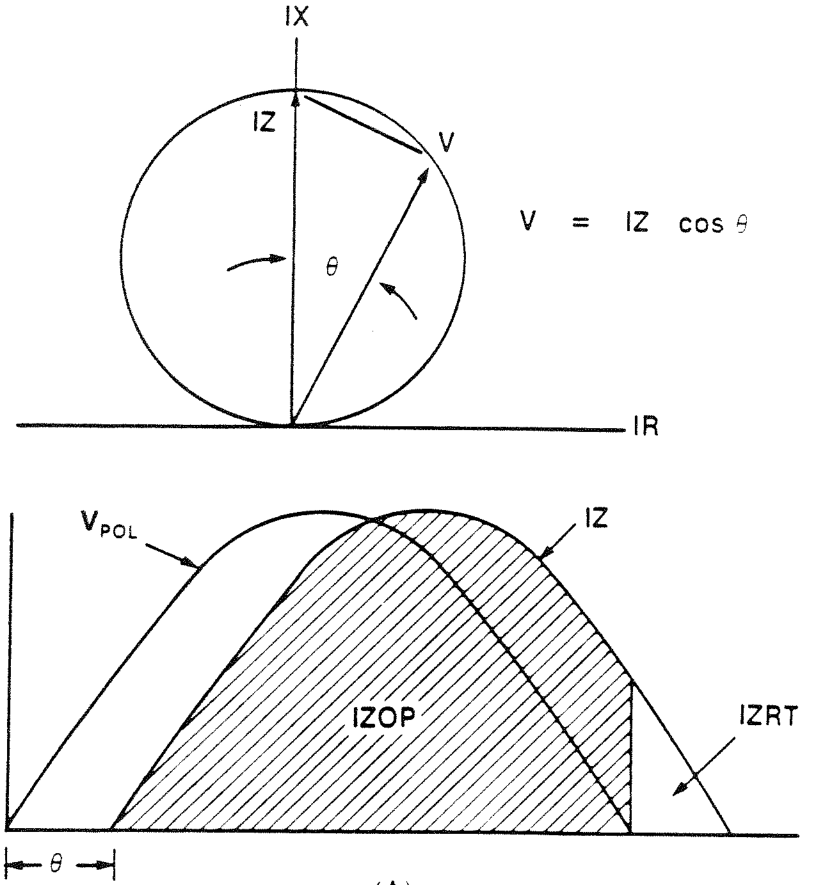


Figure 8.
PLS – Positive Sequence Distance Unit
Block Diagram



(A)

$$IZRT = IZ \int_{0}^{\theta} \sin\theta = IZ\ (1 - \cos\theta)$$

$$IZOP = IZ \int_{\theta}^{180} \sin\theta = IZ\ (\cos\theta + 1)$$

$$IZOP - IZRT = IZ\ (\cos\theta + 1 - 1 + \cos\theta) = 2\ IZ\ \cos\theta$$

$$VREST = V \int_{0}^{180} \sin\theta = 2\ V$$

BALANCE POINT:

$$IZOP - IZRT = VREST$$

$$2\ V = 2\ IZ\ \cos\theta$$

$$V = IZ\ \cos\theta$$

(B)

Figure 9
PLS – Positive Sequence Distance Unit Balance Point Condition

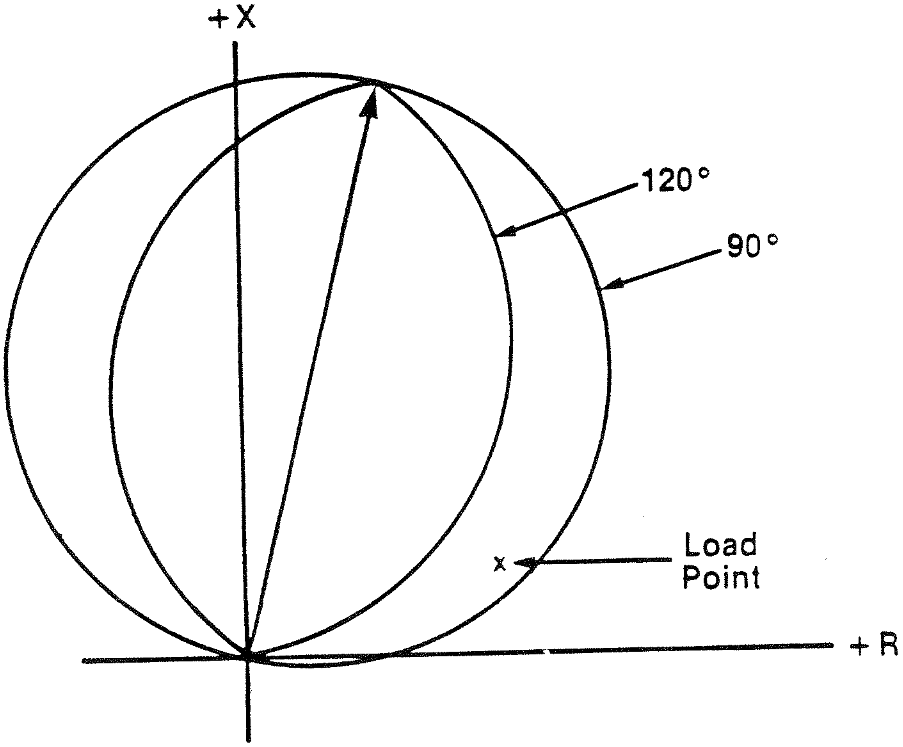


Figure 10.
MHO/LENS Characteristic