INSTALLATION • OPERATION • MAINTENANCE

INSTRUCTIONS

A VERSATILE PHASE-ANGLE METER FOR POWER SYSTEM ANALYSIS

Abstract – The phase-angle meter is an instrument that can be of considerable value to industry. It is simple to use, but there is a problem in understanding its readings. This paper endeavors to impart an understanding of its use and to clarify interpretation of results obtained.

Included is the description of a unique phase-angle meter with 360 degree scale having not only the versatility of broad current and voltage ranges for current-voltage phase-angle measurement, but including built-in circuits for measuring the phase-angle between two currents or between two voltages.

In trouble-shooting, it will expedite the solution of relay and meter connection problems by giving the phase relationships between various combinations of currents and voltages. Illustrations of typical relay circuits are included showing current directions which can be checked with the phase-angle meter. Other illustrations show devices which use both current and potential circuits, such as a polyphase watthour-meter. The phase relationships between these currents and potentials are shown with indications as to how to connect a phase-angle meter to read these relationships.

Fig. 1. Westinghouse Type PI-161 Phase-Angle Meter.

INTRODUCTIONS

The trend toward continuous manufacturing processes increases the importance of absolute continuity of electric power service. Failure to achieve this goal results in decreased profits from lost production, and the high cost involved in restart-up following a plant shutdown.

Generators, transformers, relays, and switching equipment must be coordinated in modern electrical distribution systems to assure electrical reliability. This is a complex and difficult task for field engineers and electricians. Many electrical devices require connections which depend upon the proper relationship between current and voltage to provide satisfactory operation. The phase-angle meter is an instrument which allows measurement of this relationship.

The purpose of this paper is to describe a versatile, new portable phase-angle meter and to impart and understanding of electric power system conditions through interpretation and understanding of the instrument readings by:

1. describing the new Westinghouse Type PI-161 phase-angle meter as a field instrument.
2. citing examples to illustrate use of the instrument.
3. providing a bibliography to assist engineers and relaymen using the instrument.

PHASE-ANGLE METERS

Three types of phase-angle meters are commercially available.

1. Electrodynamic: This type is accurate but has a scale limited to 90 degrees so that switching is required between quadrants.
2. Electronic: This type can be built with high accuracy but has limitations for field work, and also is limited to 90 degree quadrants.
3. Moving-iron type with 360 degree scale, which is preferable for most field work. The instrument to be described in this paper operates on this principle.

The Westinghouse Type PI-161 phase-angle meter, shown in Fig. 1, has been developed to meet the need for a portable 360-degree scale instrument incorporating a broad coverage of current and voltage ranges to measure the angle between a current and a voltage, or between two voltages or two currents. Conventional counterclockwise vector notation has been incorporated in the 360-degree scale to picture clearly the vector relationships. The scale has an effective length of about 20 inches resulting in scale resolution or readability of nearly 1/16 inch per electrical degree.

The mechanism consists of a motor-type stator with distributed 3-phase star-connected windings energized on single-phase through a phase-splitter circuit having a capacitor in one leg and an inductor in one of the other legs. Adjustable resistors are provided to adjust the current level in each leg for calibration. The moving element rotates freely with low-residual, annealed Hipernik ® nickel-iron vanes magnetized by a separate inner-coil winding. Moving element position is determined by the phase-angle between the electrical quantity which energizes the rotating magnetic field of the stator, and the electrical quantity which energizes the inner magnetizing coil. The moving-element vanes are magnetized alternately north and south by the alternating current and will come to rest at the point where the vanes have maximum pole strength as the rotating field set up by the stator sweeps by. This is of course true only when both circuits are energized from sources having identical frequencies. Should there be any difference in frequency, the moving element will rotate in the same manner as a synchroscope.

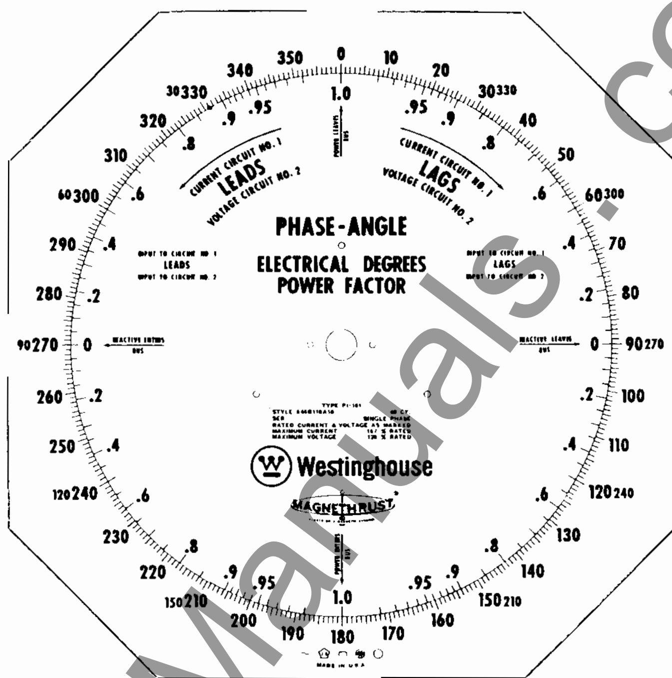

Fig. 2. Dial and scale arrangement of Type PI-161 Phase-Angle Meter.

To minimize bearing friction for improved accuracy and to provide longer bearing life with low maintenance, the conventional type bottom pivot and sapphire V-jewel, or ring bearing, has been replaced by a magnetic-suspension type of the kind used in watt-hour meters. This practically eliminates the influence of bearing friction upon accuracy, which can be appreciable for various load conditions.

Both circuits of the instrument are energized through internal multirange transformers. Circuit no. 1 is normally the current circuit and has range ratings of 30, 10, 3, and one amperes, but also includes voltage taps with ratings of 120 and 60 volts. Circuit no. 2 is normally the voltage circuit with switch-selected ratings of 480, 240, 120, 60, 30 and 15 volts,* but is also equipped with a current winding rated 3 amperes. Thus, in addition to the usual measurement of angle between a current and a voltage, the instrument is arranged to measure the angle between two voltages or between two currents. The current circuit has a maximum rating of 167 percent rated current continuously which the voltage circuit maximum continuous rating is 120 percent of rated voltage. Maximum short-time rating is of course dependent on the length of time of application. The current circuit is capable of carry-

*See Appendix II

ing an overload of twenty-times rated current for a period of two seconds. (Schematic internal wiring is shown in Fig. 25).

The rated accuracy is ± one degree at rated voltage, current and frequency. The influence of variation in voltage, current, and frequency is tabulated in the performance data and curves in Appendix I. The instrument is calibrated with current applied to circuit no. 1 and voltage to circuit no. 2. The phase-angle of the internal transformers would then introduce errors in indication when measuring the angle between two voltages or between two currents. These errors have been compensated by the addition of capacitors and resistors to maintain proper vector relationships of the instrument currents under these conditions. Compensation for phase-angle shift of the current tap of circuit no. 2 has been achieved by the addition of a capacitor and series resistor between the ± or common terminal of circuit no. 2 and the 240-volt tap of the transformer. Compensation of the transformer. Compensation of the 60-volt and 120-volt taps of circuit no. 1 has been accomplished by the addition of a capacitor and series resistor across the series resistors of these circuits.

Measurement of phase angle between a voltage applied to circuit no. 1 and current applied to circuit no. 2 is not recommended because of less-accurate compensation and reduced operating torque. Normal connection of current in circuit no. 1 and of voltage in circuit no. 2 should be used.

Synchroscopes are identical to 360-degree scale, single-phase power-factor meters, or to 360-degree scale phase-angle meters, except that they have two potential circuits (instead of one current circuit and one potential circuit). The phase-angle meter described in this paper is unique in that it incorporates two potential circuits for measuring the angular difference between two voltages, and two current circuits for measuring phase-angle between currents. The information shown on the dial will save the engineer a great deal of calculation in solving relay and metering problems.

Regardless of whether the testing involves generation, it is often convenient to assume that the source of power is a generator. Hence, the notation on the dial shown in Fig. 2.

Some engineers object to the terms *lag* and *lead*, when using a power-factor meter, because they lead to confusion if not properly defined. For example, if a current lags a voltage by 115°, it does not necessarily follow that because the current has moved beyond a 90° displacement point it automatically leads the voltage. To be sure, a current that lags a voltage by 115° also leads the voltage by 360° − 115° = 245°.

Power-factor meters are often marked *lag* and *lead* on either side of the unity mark. Occasionally *out* and *in* are substituted for lag and lead.

On a generator connected to a system supplying power at unity power-factor with the voltage remaining constant, if *excitation is increased*, the power-factor meter *will move from unity in a lag direction.* For this condition reactive is leaving the generator; therefore, the term *out* is sometimes substituted for *lag.*

A power-factor meter connected to read load *drawn from the system* by a synchronous motor deflect in a *lead direction when excitation is increased.* For this condition, the term *in* would be used in place of *lead.* Note that this is different from the generator. It is not the concern of this paper which terms are used. The information is added only for the purpose of assisting the relayman or meterman to solve his problems.

Using a phase-angle meter for the first time is akin to learning to use a slide rule. Answers from either are questionable until confidence is acquired in using the tool. The following procedure should be followed in determining the phase relationship between a current and a voltage: First, the current terminals of circuit no. 1 of the instrument are connected with proper polarity, in series with the voltage being checked. Third, the phase relationship between the current and voltage is read. The problem then is one of understanding the current and voltage vectors in various power systems and their relationship to each other. This paper includes studies made of various relay schemes and power-system components to assist in achieving this understanding.

Certain terms will be used throughout this paper, and to eliminate confusion they are defined as follows:

1. *Power Factor* is always expressed either as a decimal-fraction or as a percent. It is the cosine of the power-factor angle.

2. *Power-Factor Angle* is expressed in degrees

mately 3 to 1 steps which should make it possible to obtain accurate readings without overloading the current circuit. Each of the current taps is rated to carry 167 percent rated current continuously without overheating or damage. Higher currents can be carried for short periods.

The voltage to the phase-angle meter can bee considerably reduced, or raised 20 percent without serious error in the reading. (Rated voltage of 120 percent can be applied continuously.) A reduction of voltage by 50 percent will cause 0.5 degree leading error with rated current applied. *The pointer lags with reduced current.* Current can be reduced to 10 percent of tap value with reasonably good results. Readings are possible with greater errors to as low as 2 percent of rated current. Thus, it is possible to obtain a reading on the 1-ampere tap with as low as 20 milliamperes. (See current influence curve in Appendix I.) For some purposes in relay work the errors involved, even though great, if understood, can be unimportant. Good judgement is required in the use of the instrument and the relayman should make tests with his instrument covering the conditions under which he works in order to know the extent of the error. With only circuit no. 2 energized, the pointer will rotate in a clockwise direction. If the current is low, the reading will err on the lag side. Extreme high current will produce a slight lead error. To reiterate, even though the lag error may be great, if readings are made on balanced 3-phase currents, in a differential circuit for example, then the error applies to each and the result is an accurate comparison. That is, the *slip* is about the same for each phase.

Good habits must be cultivated in the use of a phase-angle meter. If the two leads to either circuit are reversed, a change of 180° results. A good plan is to use color-coded leads, always applying the same color to the binding posts with the polarity mark. If clips are used, the same color should be kept in the same relative position when connecting to the equipment tested. If coded plugs (i.e., the Westinghouse red and black ammeter test plug for for Flexitest ® relay cases, or the General Electric relay test plug for drawout relays) are used, the same color should always be kept away from the relay, meter, or other equipment. Then after readings are taken, there is never any doubt as to the 180° shifts. These habits are so important that reiteration is necessary. *The same color coding system should always be used in connecting the instrument.*

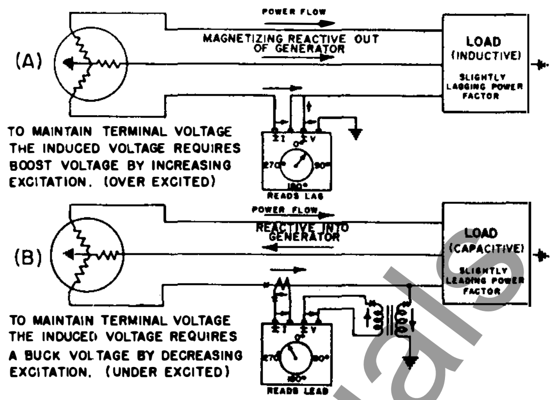

Fig. 8. Phase-angle of transmission circuit with inductive and capacitive loads.

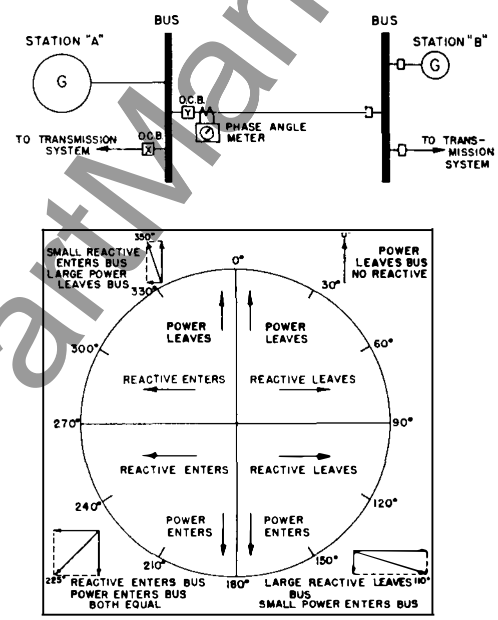

Fig. 9. Power flow, reactive flow, and the phase-angle meter.

Several uses of the phase-angle meter in industrial plants will be considered.

When a reference voltage is used, its polarity should not change due to the reversal of a convenience outlet plug. Connections to the main transformer supplying the outlet may be changed by the utility, many miles away. This possibility must always be kept in mind when taking different sets of readings at different times. *Finally, the reference voltage must be synchronized to the system on which readings are being taken.*

Real and Reactive Power Flow and the Phase-Angle Meter

The current in a transmission line as indicated by a switchboard ammeter represents both real and reactive power. An observer cannot determine whether the current is being used to produce real work or not. Almost all of the current represented may be feeding a capacitive or inductive load which produces no real work.

Figure 8 shows typical readings on a phase-angle meter for two different transmitting conditions. (A) shows that the instrument reads in a lag direction if the load takes a lagging power factor requiring the generator to be tending to boost voltage. The load is slightly inductive. (B) shows the instrument indicating *lead.* The load takes a leading power factor and requires the voltage regulator to be tending to buck voltage. The load is slightly capacitive. The average small town, with its load consisting of small motors, lights, heating elements, etc., takes a slightly lagging power-factor. A synchronous motor can be made to take either a leading or a lagging power factor depending upon its excitation. Two such motors connected to the same supply, one overexcited and the other underexcited, may have high reactive currents flowing between them. The same condition may occur with two synchronous generators.

Reference is again made to Fig. 8 (A). If a shunt reactor were the load, the phase-angle meter might read close to 90°. It would read exactly 90° if there were no copper and iron losses. If the load at (B) were an open transmission line or a bank of capacitors, the instrument might read close to 270°. The The copper loss in this case would probably be less therefore, the angular displacement from 0° would be greater than for the shunt reactor. If there were no copper and iron losses, the reading would be 270°.

It should be noted that the instruments in (A) and (B) of Fig. 8 are connected differently (one connected direct; the other through instrument transformers). The connection method (B) could have been used at (A), and the instrument would also have read a slight lag as shown at (A). Because of high voltages and currents in power systems, current and potential transformers are generally required. The resulting readings, however, will be the same.

At the top of Fig. 9 is a portion of a transmission system. A phase-angle meter, connected as shown, can read any angle on the 360° scale. The position the pointer takes will depend upon the relative direction of the real and reactive power. If both are away from the bus, the reading will be from 0 to 90°; if both are into the bus, the reading will be from 180° to 270°. If power leaves and reactive enters, the reading will be from 270° to 0°; vice versa from 90° to 180°. Further, if the power is pure reactive, the reading will be 90° or 270° depending upon direction, whether inductive or capacitive; if real power, 0 or 180°. Figure 9 shows the dial of a 360° instrument, similar to Fig. 2, with indications of where the readings will be for various conditions of power flow. The vector diagrams in the corners illustrate readings for the stated conditions. Properly connecting the instrument to obtain these readings is sometimes difficult. In the usual case, the connections are such that there is no potential present that will give a 0° reading for a unity power-factor load. The potential will usually be such that for unity power-factor load, the instrument will read lead or lag 30°, 90°, or 120°. The relayman can use a phase shifter to correct for this difference; he can mentally compensate for it in his readings; or he can use the auxiliary scale available for this instrument. This scale can be rotated to be set at the zero position to compensate for a shift due to transformer connections.

Checking Directional Relay Connections

Directional relays obtain their directional properties by selecting a current and a potential from different phases, so connected that the directional unit tends to receive maximum torque during a fault condition. Normally the current is connected so that it leads the voltage by 30, 60, or 90°. For example, for the 90-degree connection, each relay of the three involved receives a current which leads the voltage applied to that relay by 90 degrees, when the current through the relay is at unity power-factor in the tripping direction. A fault produces a highly inductive load which causes the current and potential in the relay to approach an in-phase condition for the relay which is expected to operate. It should be borne in mind that this relationship refers to the coils. If there, is an internal resistor, then this relationship does not hold true across the relay case studs.

Drawings are usually available showing the connections for a bank of directional phase relays. Information for making these drawings will come from the manufacturer's instruction books. The installation will probably have been made with the connections as indicated on the prints. The relayman may be required to determine the correctness of the installation. The final check must be made under operating conditions with primary current actually in the transmission line.

To make this check, these steps must be followed:

1. Direction of real and reactive power and power-factor must be established. The power dispatcher can tell a great deal about these conditions. During some part of every day he will probably be very certain of conditions for most transmission lines. At times, he may allow the opening of a power circuit breaker, or manipulate other equipment to assist the relayman in determining the direction of power and reactive flow. In Fig. 9, if the system feeds a normal inductive load such as a small town, and the generator circuit breaker at station B is opened, as well as circuit breaker X at station A, the real and reactive power will be leaving the station bus. Circuit breaker X is opened to force all the power out of circuit breaker Y; otherwise the other line may carry all the power to the system. The power-factor will not be far from unity, but will be lagging. It may be that the generator at station B must be kept in operation. The operator there can be requested to set it at unity power-factor by adjusting his excitation. Station A will then be supplying all the reactive. Proper manipulation of the system by exercising good judgment can generally establish a set of known conditions.

2. The intended connection, whether 30, 60, or 90° must be known. This will have been determined by the application engineer.

3. The phase-angle meter is connected to each of the three relays, one at a time, the current circuit of the instrument in series with the current-coil of the relay, and the potential circuit in parallel with the potential coil of the relay. The three readings should be approximately the same. If they are not, they should be made the same. To make them alike, sometimes a polarity change is necessary; sometimes two phases of current or potential are crossed. All the directional elements should track; that is, they should all be open or closed. If a phase-shifter is interposed between the source of potential and the relays, all elements should open or close at about the same setting of the phase-shifter. The use of the phase shifter is academic, but it is a good exercise for a beginner.

4. The correct phase difference between current and potential must now be checked. If the *power factor* is unity and the intended connection is 30° lead, then the phase-angle meter should read 330° lag of current behind voltage or 30° lead or current ahead of voltage. If the reading happens to be 90° lag, then a counterclockwise rotation of the voltage leads of 120° is necessary. If the reading is 30° lag, a clockwise rotation of 120° plus a 180° polarity change is required. Again, assuming unity power factor, if the power is leaving the station where the relays are located, the directional elements probably should be closed depending upon the tripping direction required; for power coming in, they should be open. If the elements are not as stated here, either the current or potential connections are simply reversed on each of the relays, or the polarity of the current or potential transformers changed. Care must be taken when delta connections are encountered, because changing this type of connection can result in much confusion.

If the power factor is not unity, the departure in either the lead or lag direction must be taken into consideration while taking readings or the auxiliary scale available for the instrument is used and its zero aligned with the pointer for ease in making connection change.

Every effort should be made on a new installation to have the relays connected correctly according to the manufacturer's recommendations and diagrams. To test a system, it may be convenient to build up the output of a generator, on a 3-phase fault, until proper magnitude of current is reached to make a check. Line charging current on HV long lines may supply the necessary test current.

Additional information will follow on directional relays which will further assist in checking connections.

DIFFERENTIAL RELAYS AND THE PHASE-ANGLE METER

Figure 10 to 15 illustrate several conventional relay schemes. Various normal and fault conditions are hypothetically applied to sections of a power system. These conditions produce currents which, when applied to the diagram, prove or disprove the correctness of the circuit in question. By observing the paths and magnitudes of the currents during normal conditions and internal or external fault conditions, the correctness of the wiring can be determined. These values are readily checked with the phase-angle meter and an ammeter when actual current is flowing in the systems. The arrows represent an assumed direction of single-phase current or power flow. This current will have some definite phase-angle meter reading when compared with some reference voltage. Depending upon the polarity of the transformers in question, all the current shown by one kind of arrow, either solid or dashed will either be in-phase or 180° out-of phase with the original assumed current. The relayman will generally plug into the nearest convenience outlet for the reference voltage. After checking all the circuits of one phase, a 120° shift will be indicated on the scale of the phase-angle meter when the next phase currents are checked, if the same reference voltage is used. The magnitudes represent steady-state values of ammeter readings.

In all the drawings primary current is shown by the large arrows and secondary current by the small ones. The large, solid arrows represent current which produces secondary currents as shown by the small solid arrows. The large arrows with long dashes are accompanied by small arrows with long dashes. Similarly all the large and small arrows with short dashes are related. If the magnitude of the primary current is given, then the value of the secondary current is established by the indicated current transformer ratio. If primary current is assumed to pass entirely through the differential; that is, if the same amount of current enters and leaves the protected circuit, then no secondary current is produced which will cause the differential to operate. If a fault is assumed to occur within the protected section, then secondary currents should pass through the operating element of the relay to operate the differential control circuits to clear the faulted section. These conditions are true if the circuit is properly connected. By assuming faults as shown in the figures, any similar circuit diagram can be checked for correctness.

Some engineers insist that the reason for an error should be determined before making a change. This is excellent practice except that some field conditions demand an immediate solution. If such an expedient is taken, then the problem should be analyzed later when time permits.

Figure 10 illustrates a bus section protected by a neutral differential. In Fig. 10, if a balanced 3-phase load of 100 amperes on each conductor were being supplied through the bus section shown, no secondary current would leave either transformer bank because the currents from each bank would balance out. If the 2-ampere current shown flowing past the relay is to be actually present in the circuit, the secondaries of the current transformers of phases 2 and 3 of each transformer bank would have to be short-circuited and disconnected from the rest of the circuit. This would produce the same condition that might exist during a phase-to-ground fault external to the bus section protected. The double-headed arrow indicates that there is zero current in the relay. It can readily be seen that if the leads from either bank were crossed, the 2 amperes from each bank would be forced through the relay causing a total of 4 amperes to flow through its operating element. If, under these conditions, the induction relay were set at a low enough current value, the relay would operate on an external fault causing a misoperation. An internal fault is shown being supplied by primary current coming in through both oil-circuit breakers. The large broken arrows indicate the direction of flow, and the small arrows show that 20 amperes flow to operate the relay.

To check the circuit of Fig. 10, a relay test set could be connected to pass a single-phase current through the primary circuit to simulate a through line-to-ground fault condition. If the current transformer ratios happened to be incorrect, current would pass through the operating element of the relay. By checking with a phase-angle meter, the phase relation of the currents in question can be proved to be correct, then the ratios should be corrected. The phase-angle meter is a most valuable tool for checking differentials. Connecting it in the various circuits will establish the relative direction of currents. A sensitive low-burden (thermocouple) ammeter is also necessary to determine the magnitude of current, and should be capable of indicating very low currents. Many low-current ammeters have high internal impedance. A check will show whether the ammeter seriously affects the circuit impedance.

If a check during operation is necessary it can be done by short-circuiting and disconnecting two current-transformers in two phases, allowing the transformers in the other phase to produce a current which simulates a single-phase to ground external fault. More simply one set may be short-circuited and disconnected in one phase. The resulting current will be the vector addition of the other two which is the reverse of the one disconnected, if the power load is balanced.

Figure 12 shows the secondary currents resulting from the various primary currents entering and leaving the bus. To check the circuits under these conditions, one current-transformer from each bank is disconnected at a time, and the results observed with phase-angle meter and ammeter. If all currents coming *in* are disconnected first, the current in the relay will build up to a maximum and then decrease to zero as the *out* currents are disconnected. Actually, the current in the relay will seldom become zero, due to inaccuracies of the current-transformers. A zero reading should be viewed with suspicion as the relay may be short-circuited from the rest of the circuit. This differential may also be checked by using a relay test set for passing primary current through each current transformer, and reading the secondary current and relative phase-angle. If the same lead of the test set is always connected on the line side of the current transformers throughout the entire test, the secondary currents from each bank will all have the same relative phase relationship. This test will also check the current-transformer ratios. The 69/138-kV transformer bank has a current ratio of 2 to 1. The current-transformer ratios on the two sides are different to compensate for this power-transformer ratio difference.

Phase Differentials

Figure 11 shows that whenever primary current is present, there will be secondary current in the relays. This simplifies the check of the circuit. Modern relays provide easy methods of access into the relay circuits. If the current entering the restraining element is in phase with and equal to that leaving, then the circuit for that relay is probably correct. By reading the magnitude of the line current and knowing the current-transformer ratios involved, an approximate estimate of the actual current can be made. If the same reference voltage is used, the currents in one relay will be 120° out of phase with the other two. Slight amounts of current in the operating winding is normal, as it was in the neutral differentials. Any appreciable current will probably indicate that something is incorrect.

Figures 13 and 14 show a phase differential protecting a generator and a wye-delta transformer. The *vector voltage diagram* for the power transformer establishes the polarity of the windings of the transformer. This diagram is the standard one found on the nameplate of all power transformers. It means that in these figures, the voltage from ground or neutral to *H*1 is in phase with the voltage from *X*2 to *X*1. From the vector diagram, the direction is the same from the center of the wye to *H*1 as it is from the points on the delta *X*2 to *X*1. Observing the windings themselves it is seen that voltage on the winding at the top left of the power transformer, reading from bottom to top, is *X*2-*X*1. The vector diagram indicates that this is in phase with the voltage from the neutral point to *H*1. Because the vector diagram gives this relationship, the polarity marks are added as shown in the circles. If the vector diagram has been drawn such that the *H*1 vector was as shown in the dotted box at the upper right of the power transformer in Fig. 13, the second polarity mark would have been on the grounded side of the wye winding. The other two windings of the other two phases are similarly polarized. Assuming primary currents for faults 1 and 2 in Fig. 13, one at a time, the secondary currents will be as shown and will not pass through an operating element. Fault 3, if traced out, would act as the other two. Fault 4, however, is legitimate trouble for this circuit. There is no current in the current transformer connected to *H*3, assuming that there is no other source of power connected to the transmission line. Therefore, the secondary current from the other current-transformers is not balanced out, and the phase 1 and 3 relays operate. If fault 5 occurs, there would have been current in only the current transformer in the *X*3 circuit. This would have produced an operating current in the phase 3 relay. The path would have been through the neutral lead from wye connected current-transformer bank to the operating element of this relay. By using the same methods as used for phase differentials, these circuits can be checked by using a phase-angle meter, ammeter, and possibly a relay test set as a source of test current.

Figure 14 shows an incorrect connection and the paths of the resulting currents. A unique condition occurs with this circuit. Observing the path of the secondary current for fault 1, if only the one single-phase to ground test were made, the circuit would appear to be correct, because current does not go through an operating element. It actually follows the same path as that of fault 1 in Fig. 13. The second test shows that the circuit is in error. If the circuits were so connected, an external phase to ground fault on phase 1 would not trip the differential, and thus indicate that the circuit was correct. This could have resulted in the assumption that the entire differential was correct.

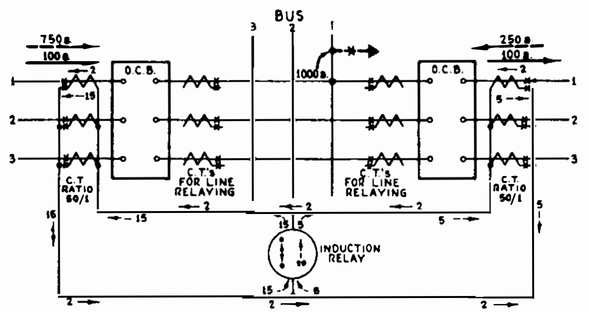

Fig. 10. Overcurrent relay in a bus neutral differential relay scheme.

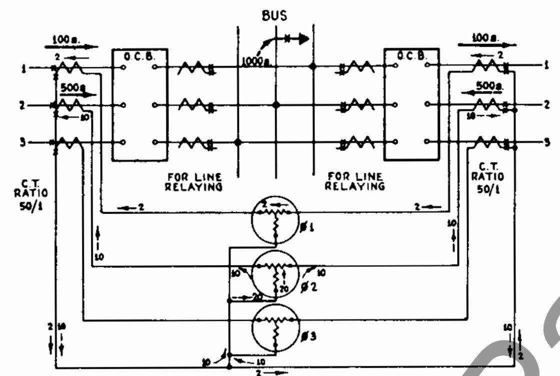

Fig. 11. Three-phase bus differential relay scheme.

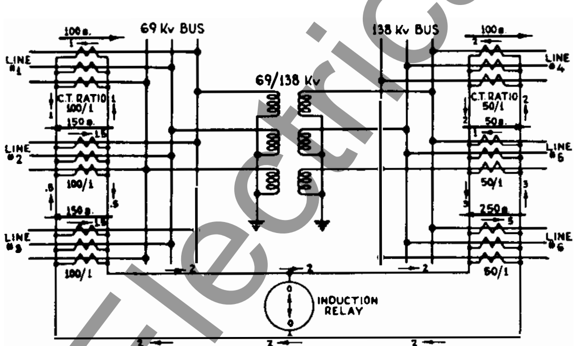

Fig. 12. Overcurrent relay in a transformer neutral differential scheme.

Figure 15 illustrates a method of protecting a large-generator installation. Any fault within the protected section will operate the transformer differential. To operate the generator differential, a fault must occur between the Y connected current transformers at the transformer, and those in the neutral connection of the generator.

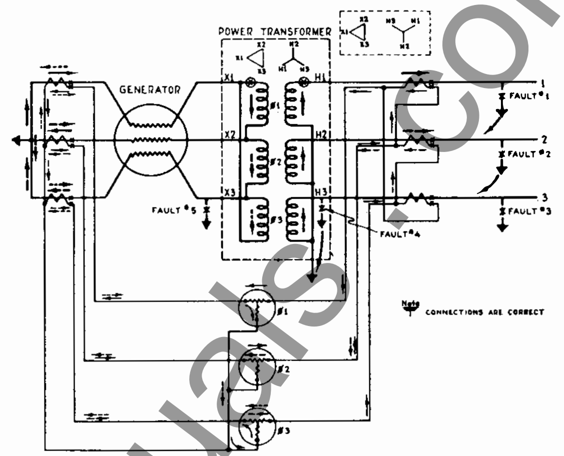

Fig. 13. Three-phase transformer differential scheme correctly connected.

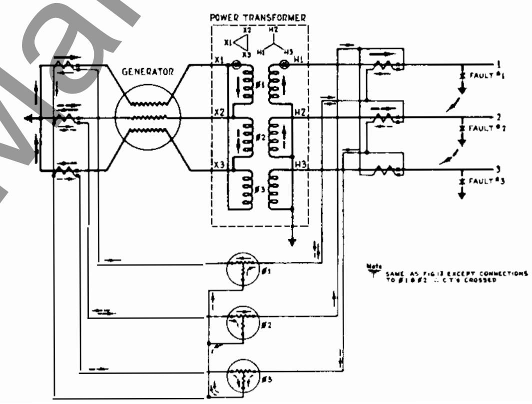

Fig. 14. Incorrect variation of Fig. 13 which under some conditions may appear to be correct.

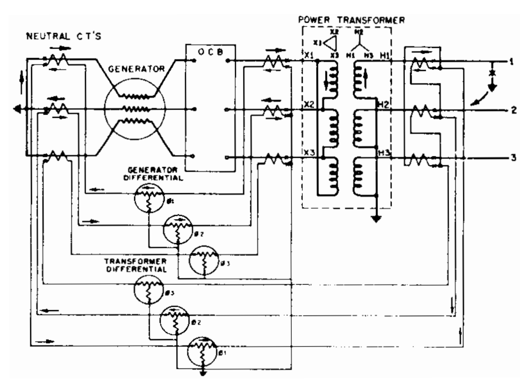

Fig. 15. Three-phase generator and transformer differential relay scheme.

Balancing Transformers

Figure 16 shows the use of the balancing transformer, and how it functions. The conditions at both (A) and (B) are identical except that a different type of balancing transformer is used. It should be noted that the ampere-turns balance out in each case.

A phase-angle meter and an ammeter connected in these circuits with a test primary current through the current transformers as shown would verify correct connections and polarities. Under operating conditions, disconnecting and short-circuiting the proper current transformers would accomplish the same result.

Checking Schematic Diagrams of AC Circuits

Figures 17 and 18 illustrate a vector analysis of a 3-winding power transformer differential and a bank of directional relays. (A) and (B) are added to show the relationship between polarity and current direction. The circuits would not be affected if both polarity marks were moved to the opposite ends of the windings. Further, direction of the polarity arrows is arbitrary and could just as well have been pointed in the other direction, but when once established should be maintained throughout a problem. When pointing in the same direction they mean that current flowing in the two windings is in phase. The heavy arrows indicate current direction.

To check the differential circuit, these steps are followed:

1. It is assumed that power is flowing into the power transformer at the 138-kV terminals and flowing out at the 69- and 12.5-kV connections. Some other assumptions could have been made. However, the power going in at one voltage must be coming out at another.

2. Polarity marks are added to the transformer windings by observing the nameplate *vector voltage diagram.* This will be done in the same manner as stated previously. See Fig. 13 and the accompanying text. The same notation is added to the windings as found on the polarity diagram. The diagram indicates that the polarity relationships of the windings are neutral to *H*1, and *Y*2 to *Y*1; N to *H*2,; and *Y*3 to *Y*2; *N* to *H*3, and *Y*1 to *Y*3.

3. For the purpose of adding the arrows to the drawing to indicate the direction of current flow, it is assumed that in each primary phase the current follows the power as mentioned previously.

4. Current direction is established in all the secondary circuits starting with the assumption stated in item 3.

The direction of current from the 12.5-kV tertiary of the power transformer to the relay is

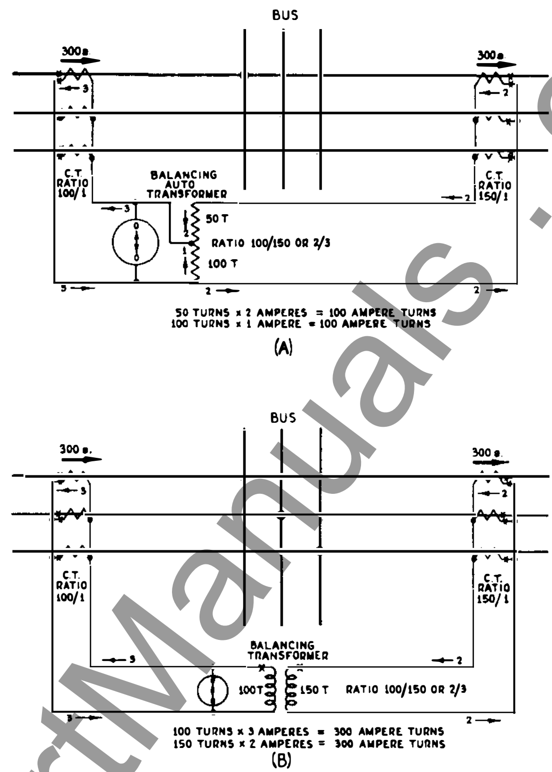

Fig. 16. Two types of balancing transformers showing direction and magnitude of currents.

evident because of the assumption that power is flowing out. The current from the two auxiliary transformers to the relay is not evident because of the delta connections of the banks. Since the current is flowing out of the transformer at both the 69-and 12.5-kV terminals and because the current from the 12.5-kV tertiary winding is into the relay, then that of the 69-kV is also into the relay. With both of these currents going in, the current must be flowing out of the relay to the 138-kV circuit. A phase-angle meter connected into these circuits will give this indication.

5. The small circles at the junction points of all the delta connections contain arrows indicating direction of current at these points. From these arrows, an equation may be written for the delta current in terms of the wye-currents. The large circle to be defined at the top of the drawing. *Ih*1 Δ is seen to split into two other currents, *Ih*3 and *Ih*1. As *Ih*1 is away from *Ih*1 Δ, it is called positive and as *Ih*3 is toward it, it is negative. The equation is written as shown on the delta lead to the relay emanating from the junction point. Equations are also shown for the other phases of the 138-kV circuits. Those for the delta currents from the 69-kV circuits

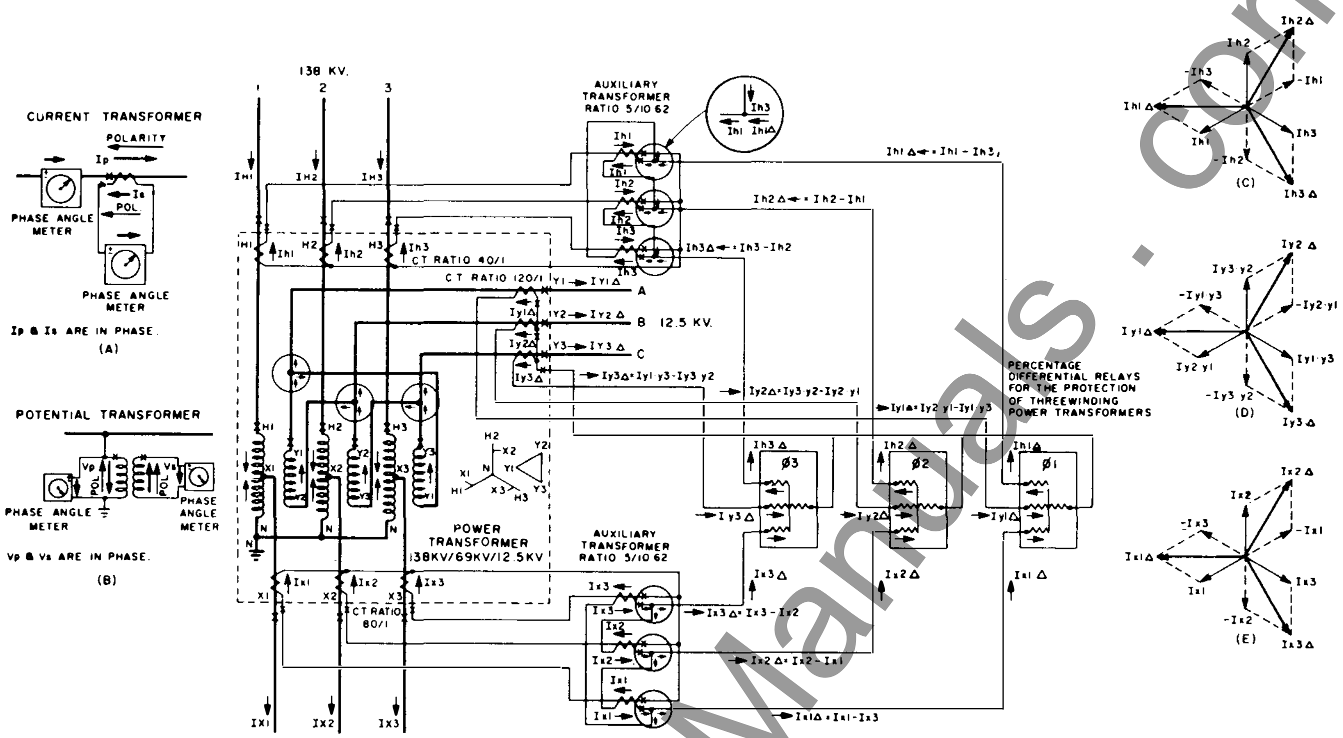

Fig. 17. Analysis of current flow in a transformer differential relay circuit.

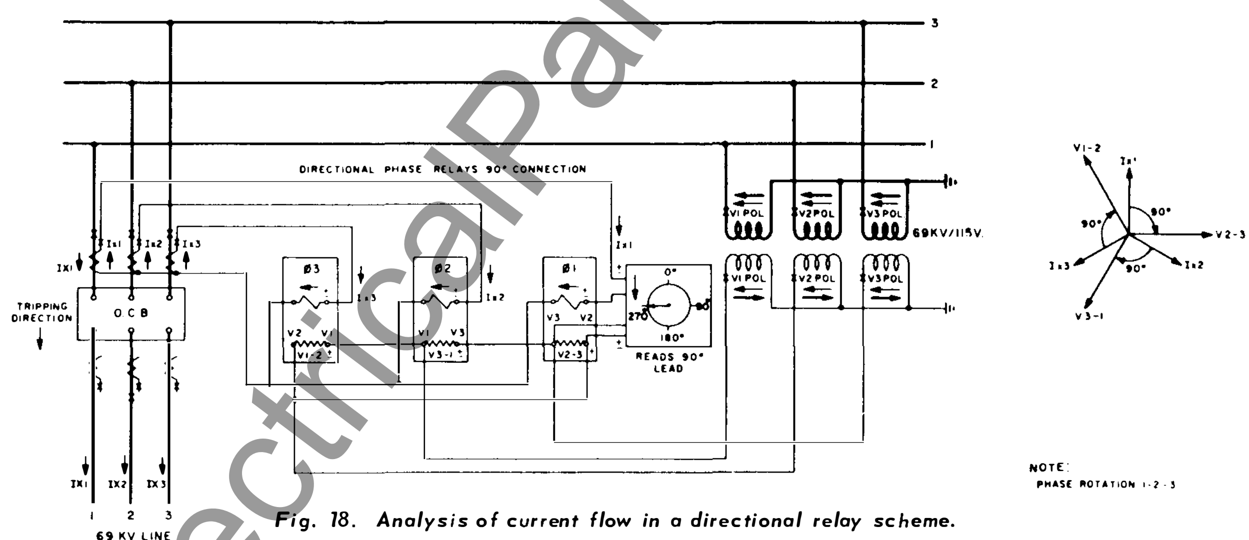

Fig. 18. Analysis of current flow in a directional relay scheme.

and for the delta currents from the tertiary winding are similar except that the notation for latter is a little different. In order to preserve the notation that was used on the nameplate of the power transformer, the tertiary winding current for phase 1 is called $1Y2.Y1$ reading from bottom to top. The other two phases are similar.

In all cases when passing through the wye-connected current-transformer banks, the current transformer banks, the currents remain in phase. To indicate that the current has passed through a current-transformer bank that the phase relationship remained constant, the notation was simply changed from *IH*1 to *Ih*1. This was done on all three voltage circuits.

6. The vector diagrams constructed from the equations are shown at (C), (D), and (E). In vector diagram (C) $Ih1\ \Delta = Ih1 - Ih3$. Vector *Ih*3 is reversed as drawn with a dotted line at

(C) to show that it is a minus or negative value. The parallelogram is completed and $Ih1\Delta$ drawn in. Phases 2 and 3 can be completed in the same way. (D) and (E) are similarly constructed. If the final delta currents $Ih1\Delta$, $Iy1\Delta$, and $Ix1\Delta$ for phase 1 are all in phase, and the same condition exists for phases 2 and 3, then the differential circuit is correct. The equations for the 12.5-kV secondary currents are written in the secondary system, but are exactly the same as if they were written in capital letters for the primary system; i.e., $Iy1\Delta = Iy2.y1\text{-}Iy1.y3$ is equivalent to $IY1\Delta = IY2.Y1\text{-}IY1.Y3$.

To check the ratios of the auxiliary current transformers, Table I is a guide. The *V or I ratios* indicate that if all the current is flowing from the 138- to the 69-kV terminals, there will be twice as much current in the 69-kV as in the 138-kV bank. Similarly, if all current flows out of the 12.5-kV terminals, there will be 11.04 times the 138-kV current in the 12.5kV circuit. For ease of calculation the *assumed I* in the 138-kV circuit is such that one ampere is the output of the secondary of the 138-kV current transformer. As stated in the notes, the ratio of one auxiliary is checked by first assuming that all the current flowing in the 138-kV circuit flows out of the 69-kV circuit. After the value of secondary current is obtained, then it is assumed that all of the current flows out of the 12.5-kV winding to obtain the other secondary current. The assumption has a basis in fact, in that if either of the lower-voltage circuits is opened,the assumed condition will actually exist. The "ratio change due to wye-delta connections of auxiliary current-transformers" is an increase in current due to the conversion from wye to delta in the auxiliary current-transformer bank. The resulting delta current of a delta hookup is always the square-root of three times the current in the winding. The value of 5 is used in the final ratio because this value has been arbitrarily used by the industry as the current which will, for example, give a full-scale reading on a standard switchboard ammeter. Also, current-transformer ratios are normally given as some primary value to 5.

ADDITIONAL INFORMATION ON DIRECTIONAL RELAY CONNECTIONS

The connections for directional-phase relays (see Fig. 18) are determined by the manufacturer of the relay, because only he knows how the internal windings of the relays are brought out. The relayman can check the angular connection from the manufacturer's diagram. He can determine if it is 30°, 60°, or 90°, and if the phase-shift is either lead or lag. The 90° connection is almost the only one now in use. In this case, the potentials are 90° behind the currents. The voltage on any of these relays is the vectorial difference of the two phase-to-ground voltages attached to it. The phase shift can be established as well as the correctness of the make up of the delta. The directional contacts themselves may establish the correctness of the current transformer connections if the direction of power flow is known. Some relays carry polarity marks as indicated, and assist materially in their check. For a unity power-factor load the phase-angle meter, as connected, will indicate a 90° lead for this connection.

TABLE I

DETERMINING RATIO OF WYE-DELTA AUXILIARY CURRENT TRANSFORMERS FOR PHASE-ANGLE AND CURRENT CHECKS

θ to θ voltage	138 kV	69 kV	12.5 kV
V or *I* ratios	1	2	11.040
Current transformer ratios	40/1	80/1	120/1
Assumed *I*	40 A	2 × 40 = 80 A	†11.04 × 40 = or 441.6A
Secondary *I* from current transformer	1A	1 A	$\frac{441.60}{120} = 3.680A$
★Ratio change due to wye-delta connection of auxiliary current transformers	$\sqrt{3}$ or 1.732	$\sqrt{3}$ or 1.732	3.680
Reducing to unity	1	1	$\frac{3.68}{2.124\sqrt{3}} =$
‡ Ratio of final auxiliary transformers	5	5	5 × 2.124 = 10.62

Figure 19 shows the method of connecting a phase-angle meter in a typical line circuit when the potential transformers are connected wye-wye.

If only delta potentials are available, the measurement of power-factor angle or phase angle is more complex, because the voltage reference is shifted 30° leading or lagging. Figure 20 shows the proper connections when only delta potentials are available.

With the connections as shown, that is, with the phase-angle meter potential polarity connected to the same phase as the current, and the potential nonpolarity connected to the phase which lags, the phase-angle meter will read 30° lagging when the line current is leaving the bus at unity power factor. If the nonpolarity of the phase-angle meter's potential element is connected to the leading phase, then the same line current condition will be indicated when the phase-angle meter reads 30° leading. This relationship is easy to remember: potential polarity always on the current phase, nonpolarity on lagging phase gives reference 30° lagging, nonpolarity on leading phase gives reference 30° leading.

These instructions have been written from the point of view that the current and potential transformer connections and polarities are known. This is essential if line current conditions are to be determined by phase-angle meter readings. If connections and polarities are to be determined, then the line-current conditions must be known. For 60° and 90° connections the same reasoning applies.

RECTIFIER TRANSFORMER CHECKS

Figure 21 illustrates the problem of connecting the single-phase transformers of a 3-phase full-wave rectifier. If the primaries of two transformers are connected between phases 1 and 2, their secondaries will be either in-phase or 180° out-of-phase with the primary. The secondaries are chosen to agree with the drawing. Secondary connections will be as illustrated if potential connections to the phase-angle meter are taken from each secondary winding such that the degree readings are as shown on the upper left-hand part of the illustration, if the polarity mark is always connected away from the neutral point. The two potential windings of the phase-angle meter will be required for this test. The instrument is polarized with any convenient voltage

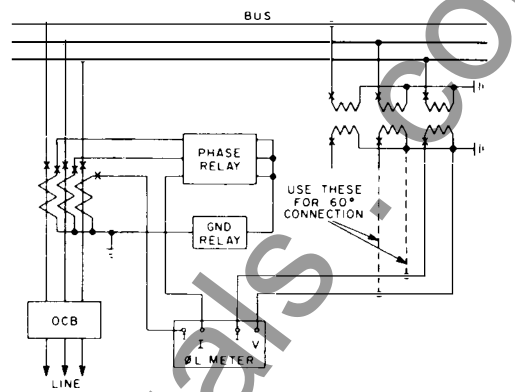

Fig. 19. Phase-angle meter connections in a Y-connected potential, directional relay scheme (potential connections to relays ommitted for simplicity).

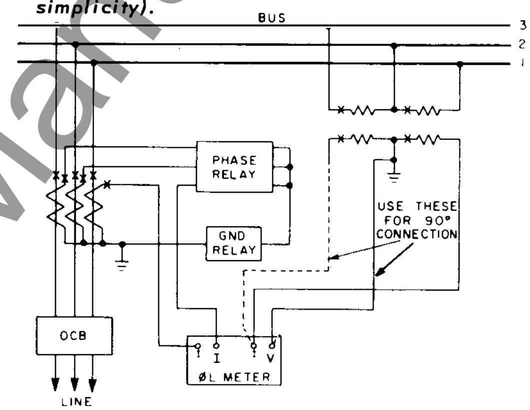

Fig. 20. Phase-angle meter connections in a Δ-connected potential directional relay scheme(potential connections to relays ommitted for simplicity).

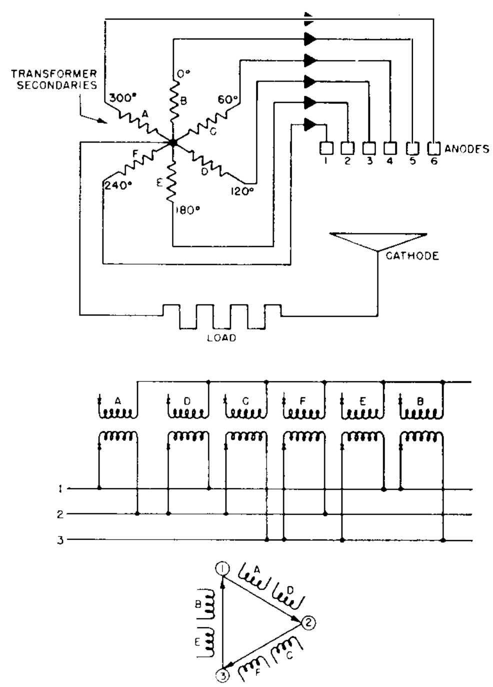

Fig. 21. Analysis of single-phase transformer connections in a 3-phase full-wave rectifier.

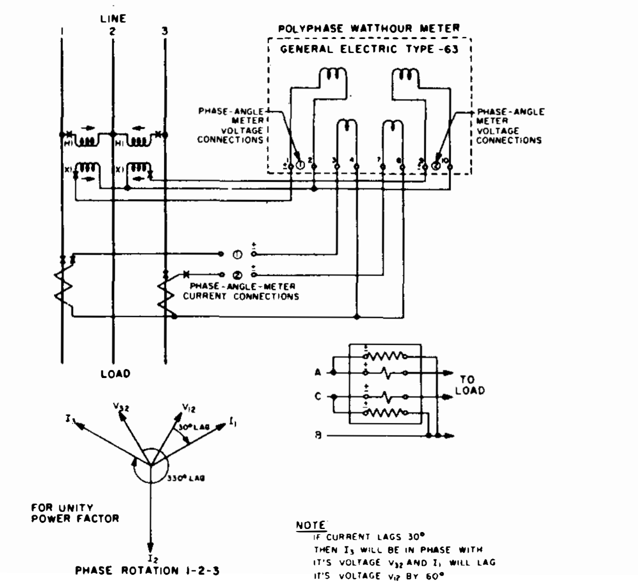

Fig. 22. Analysis of polyphase watthour-meter connections.

that is synchronized with the power to the rectifier. The readings may not be as shown, but the angular relations will be the same. This is because the source of power to the polarizing element of the phase-angle meter may be out-of-phase with any one of the secondary potentials being measured. The auxiliary scale is used and the 0° mark aligned on the auxiliary scale with the pointer for the first reading. The 60° shift as the rectifier transformers are checked will then be readily apparent. If the rectifier has twelve transformers instead of six, the shift will then be only 30° and the auxiliary scale will then be even more helpful.

CONNECTIONS FOR POLYPHASE WATTHOUR METERS

Figure 22 illustrates the problem of checking out watthour meters, watt meters, reactive kVA meters, and any other types of meters or instruments which use currents and potentials in specific relationships.

If the phase-angle meter is connected as shown in the drawing, the instrument will check the existing relationships against the vector diagram of the instrument.

MISCELLANEOUS CHECKS

In connecting a group of potential transformers for a synchronizing system, the various potentials can be checked to be sure they are on the same phase and that polarities are correct.

Phasing can be checked by comparing potentials. Phases that will be connected together should have the same phase relationship. Phase rotation can be checked to see which phases follow each other.

Scott-connected transformers can easily be checked to determine phase relationships by comparing each voltage with some reference.

Each of the above requires some other potential to polarize the instrument. Care should be exercised that the load supplies current that is close to the rating of the instrument. Caution should be exercised to not pick a polarizing voltage which is connected to another power system, because the phase-angle meter will then never read a single value, but will continue to change as the systems go in and out of phase. This suggests that the phase-angle meter can also be used as a synchroscope. It makes a good substitute.

When the current elements of several devices are connected in series, such as the protective relays and meters used on a large motor, an ammeter and a phase-angle meter can be connected to a test plug and inserted in one relay and/or meter after another to quickly check the presence of current, and phasing through the whole group of devices.

APPENDIX I

Characteristics and Performance of Westinghouse Type PI-161 Phase-Angle Meter

Rated Accuracy	Within one degree at rated voltage, current, and frequency.
Scale Length	21 inches (53cm). Scale displays all 4 quadrants or 360 degrees. One degree equals 0.050 inches (1.48 mm.).
Response Time	2.5 seconds maximum at rated current and voltage.
Damping Factor	2.5 minimum at rated current and voltage.

Loss	Refer to "Line loss and instrument current" table.
Bearing System	Magnetic suspension.

Circuit No. 1 (Current)

Self-contained ranges.	30/10/3/1 Amp. and 120/60 volts.
Maximum continuous current	167% of rated.
Current influence with rated voltage on circuit no. 2	See Fig. 23.
Current influence with rated current on circuit no. 2	See Fig. 29.
Voltage influence with rated voltage on circuit no. 2	See Fig. 30.
Minimum pickup for positive reading	2% of tap value.

Circuit No. 2 (Voltage)

Self-contained ranges.	480/240/120/60/30 Volts and 3 Amp.
Maximum continuous voltage.	120% of rated.
Voltage influence with rated current on circuit no. 1	See Fig. 26.
Voltage influence with rated voltage on circuit no. 1	See Fig. 28.
Current influence with rated current on circuit no. 1	See Fig. 27.
Frequency Influence	See Fig. 24.
Dielectric Test	2600Vrms live parts to test probe.
Dimensions	Length 12.63 inches (32 cm) Width 11 inches (28 cm). Depth 8.32 inches (21 cm).
Weight	20.5 pounds (9.3 kg.)
Case	Mahogany core with plastic rosewood finish veneer.

APPENDIX II

Protective Circuit

Potential circuit (circuit number 2) is protected from overvoltage damage by the combination of a fuse and an overvoltage sensing circuit. These are shown as part of the internal schematic wiring in Fig. 25. If operation is accidentally attempted at a voltage exceeding the switch setting; the protective circuit will function and prevent damage to the internal potential transformer. For proper operation it is essential that only the fuse specified on the instrument panel be used. The use of a higher current fuse will nullify the action of the protective circuit and upon overvoltage, both the protective circuit and the internal transformer may be damaged.

OPERATIONAL TESTS

1. Apply voltage only to circuit no. 2. Pointer should rotate slowly in a clockwise direction.

2. Apply the same rated voltage to both 120-volt voltage circuits (no. 1 and no. 2) observing proper polarity. The pointer should indicate within one degree of zero on the scale.

3. Connect the 3-ampere ranges of circuits no. 1 and no. 2 in series, adjusting the current to 3 amperes ± 0.2 ampere observing proper polarity The pointer should indicate within one degree of zero on the scale.

CALIBRATION CHECK

Calibration should be checked at 120 volts, 60 Hz. on circuit no. 2, and 3 amperes on circuit no. 1 against a known standard. Under these reference conditions, the calibration should be within one degree plus or minus throughout the scale. Calibration adjustments should be made only after it has been determined that the instrument is out of calibration. Three adjustments are involved in adjusting the calibration.

1. Orientation of the pointer on the shaft: The pointer is secured to the moving element shaft by means of two oppositely located set screws. In positioning the hub longitudinally (vertically) on the shaft, make certain that the lower face of the pointer hub clears the upper bearing screw shoulder when the pointer hub is depressed against the lifting force of the

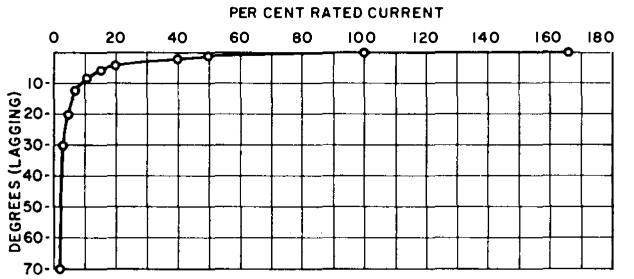

Fig. 23. Type PI-161 Phase-Angle Meter, current influence.

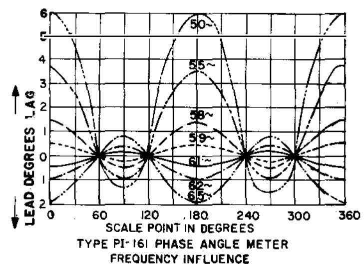

Fig. 24. Type PI-161 Phase-Angle Meter, frequency influence.

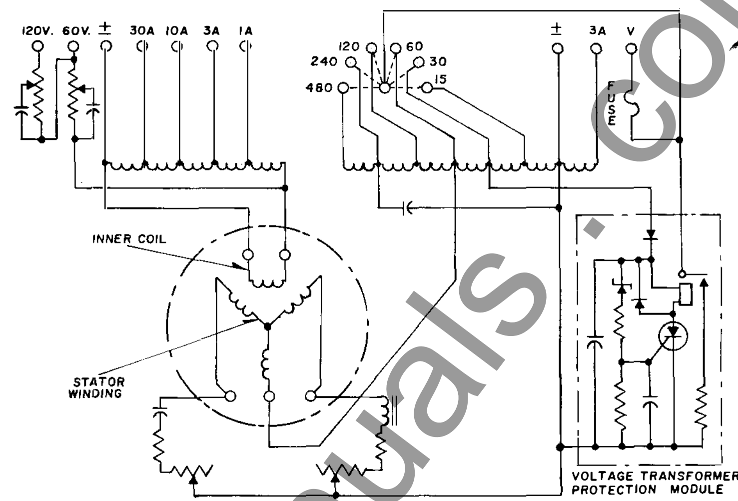

Fig. 25. Type PI-161 Phase-Angle Meter, schematic internal wiring.

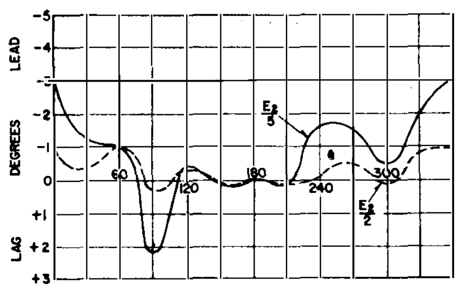

Fig. 26. Type PI-161 Phase Angle Meter, voltage influence, circuit no. 2 (rated current applied to circuit no. 1), voltage influence characteristic.

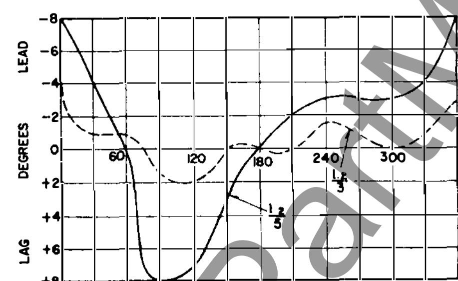

Fig. 27. Type PI-161 Phase-Angle Meter, current influence, circuit no. 2 (rated current applied to circuit no. 1), typical current influence characteristic.

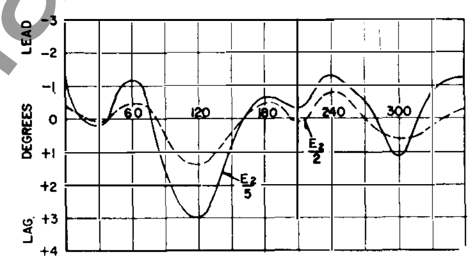

Fig. 28. Type PI-161 Phase-Angle Meter, voltage influence, circuit no. 2 (rated voltage applied to circuit no. 1), typical voltage influence characteristic.

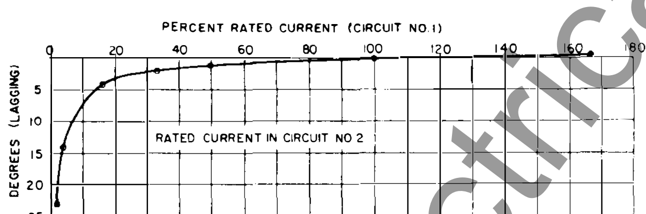

Fig. 29. Type PI-161 Phase-Angle Meter, current influence, circuit no. 1, current-current angle measurement.

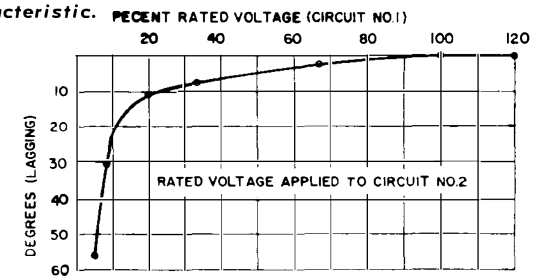

Fig. 30. Type PI-161 Phase-Angle Meter, voltage-voltage angle measurement, voltage influence circuit no. 1.

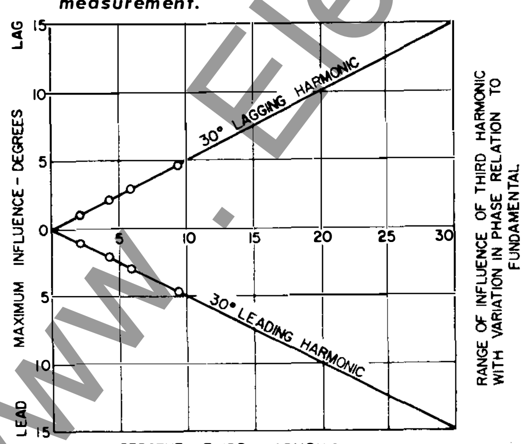

Fig. 31. Type PI-161 Phase Angle Meter, influence of third harmonic in current circuit (all angles based on 60 Hz.)

REPAIRS AND RENEWAL PARTS

Repair work can be done most satisfactorily at the factory, or at any authorized Instrument Repair Facility (see Service Directory 43-000). However, interchangeable parts can be furnished to the customers who are equipped for doing repair work. When ordering parts always give complete nameplate data.

Magnethrust® bearing. Initially, the set screws should be tightened lightly only to the point of securing the pointer vertically, Then, if necessary, any radial adjustment to position the pointer to a division mark on the scale can be made by giving the pointer a "flip" or spin with the finger. This will move the pointer in the direction of spin. With a few trials, it is possible by this technique to position the pointer to a specific point on the scale. The set screws should then be tightened securely.

2. Location or "squaring" the dial for concentricity of scale distribution: Dial screw holes are oversize to permit shifting the dial to equalize scale quadrants. After the pointer has been adjusted to indicate zero at zero phase angle, a reversal of the current should result in an indication of 180 degrees. Also, an angle of 90 degrees with reversal should result in indications of 90 and 270. The dial should be shifted as necessary to obtain this result, and the dial screws tightened.

3. Current level adjustment of the split-phase circuit: Insert low-resistance milliammeters (0-100 or 0-200 mA) in the capacitor leg and in the inductor leg of the instrument circuit. Current levels should be adjusted to equality by resistance adjustment of each lag. With 120 volts, 60 Hz. applied to circuit no. 2, the trial current setting of each leg should be about 66 mA. Check the scale distribution with the standard. Normally, the points 0, 90, 180 and 270 will be on with proper pointer setting. The points in between will read high if the split-phase circuits have too high a current level, and vice versa. Adjust as required to obtain tracking throughout the scale.

COMPENSATION CHECK

After calibration has been checked with current to circuit no. 1 and voltage to circuit no. 2, a check should be made of the compensation for measuring voltage vs. voltage and current vs. current.

1. Compensation for correct indication of the angle between two voltages is accomplished by capacitors connected across a portion of each of the resistors in circuit number 1 as shown in Figure 25 (60 volt and 120 volt terminals).

   With 60 volts, 60 Hz. across circuits number 1 and 2 in parallel, the pointer should indicate within one degree of zero. Small corrections in compensation can be made by adjusting the position of the sliding contact on the resistor in the 60 volt circuit. Changes in compensation beyond this range of adjustment will require a larger value of capacitor. The next larger value will usually be satisfactory.

   The procedure for the 120 volt range is similar to the 60 volt range above except the resistor tap and capacitor involved are those in the 120 volt circuit.

2. Compensation for correct indication of the angle between two currents is accomplished by a capacitor across the ± and 240 volt points of circuit number 2. If the pointer does not indicate within one degree of zero with 3 ± 0.2 amperes through both circuits in series, the compensation has changed and should be corrected. The correction is made by changing the trimmer (small) capacitor and/or the main capacitor across the ± and 240 volt points until the pointer indicates properly.

LINE LOSS AND INSTRUMENT CURRENT

Nominal Values for Reference

Circuit No. 1

Applied	Loss	Voltage on KI-261	KI-261 Instrument Current
120 V.	65- 75 mA	—	60- 75 mA
60 V.	65- 75 mA	—	60- 75 mA
30 Amp.	70- 90 mA	—	190-210 mA
10 Amp.	170-210 mA	—	190-210 mA
3 Amp.	0.55-0.65 V	—	190-210 mA
1 Amp.	1.2 -1.7 V.	—	190-210 mA

Circuit No. 2

Applied	Loss	Voltage on KI-261	KI-261 Instrument Current
480 V.	11-13.5 mA	55-60 V.	70- 85 mA
240 V.	22-27 mA	55-60 V.	70- 85 mA
120 V.	45-55 mA	55-60 V.	70- 85 mA
60 V.	100-120 mA	55-60 V.	70- 85 mA
30 V.	195-210 mA	55-60 V.	70--85 mA
15 V.	390-440 mA	55-60 V.	70- 85 mA
3 Amp.	0.42-0.48 V.	24-30 V.	33- 39 mA

WESTINGHOUSE ELECTRIC CORPORATION

RELAY-INSTRUMENT DIVISION **NEWARK, N. J.**

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