Requirements for Phase Angle Measurement

- The phase angle meter is a valuable tool for verifying the proper installation of medium- and high-voltage primary metering equipment and sophisticated protective relays that receive input from Potential and Current Transformers (PTs & CTs).
- Phase angle meters are also used to verify the correct connection of three-phase transformer banks which must be paralleled with an existing electrical bus or high voltage line. The process of making these measurements is known as “phasing-out” and is performed before the tie-in is made.
- This equipment is also used for conducting electrical system load and power factor studies. The system power factor is equal to the cosine of the phase angle (expressed as a percent) that exists between the system voltage and current. Once the system power factor is determined, the system power triangle (true power in watts, apparent power in volt-amperes, and reactive power in vars) can be developed and analyzed.
- Phase angle measurement is also employed to analyze the operation of AC synchronous generators and synchronous motors to verify the proper operation of field regulators and synchronizing equipment.

Types of Meters

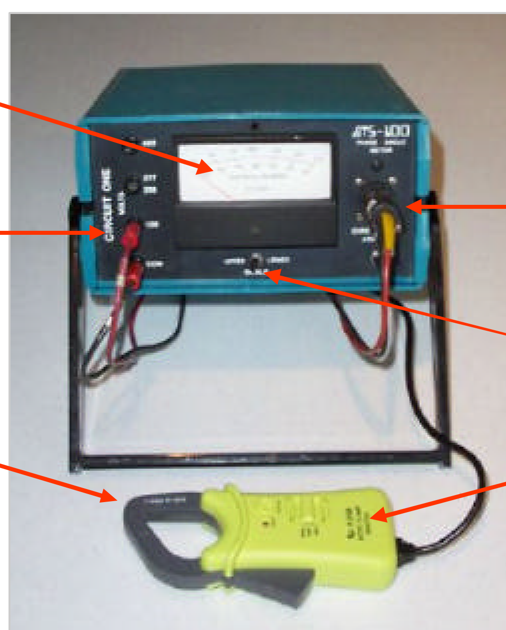
Numerous manufacturers offer phase angle meters, either as a separate metering device, or as an integral part of AC power measurement and recording equipment. The display readout is generally digital but may also be analog viewed in quadrants, analog with a circular 360° scale, or as a phasor diagram displayed on a laptop computer.

The ATS-100 Phase Angle Meter described in this article is a low-cost, easy to operate unit developed by Kilowatt Classroom LLC. It is unique in that it can measure the phase angle directly on distribution power lines to 34.5 kV using an insulated fiber optic link. Operation of the ATS-100 is similar to other stand-alone instruments and is featured in this article to illustrate the measurement procedure.

For background information on this subject see The Industrial Electrician’s Notebook™ articles: *Understanding Transformer Polarity*, and *Power in AC Circuits* on the web @ www.kilowattclassroom.com

ATS-100 Phase Angle Meter

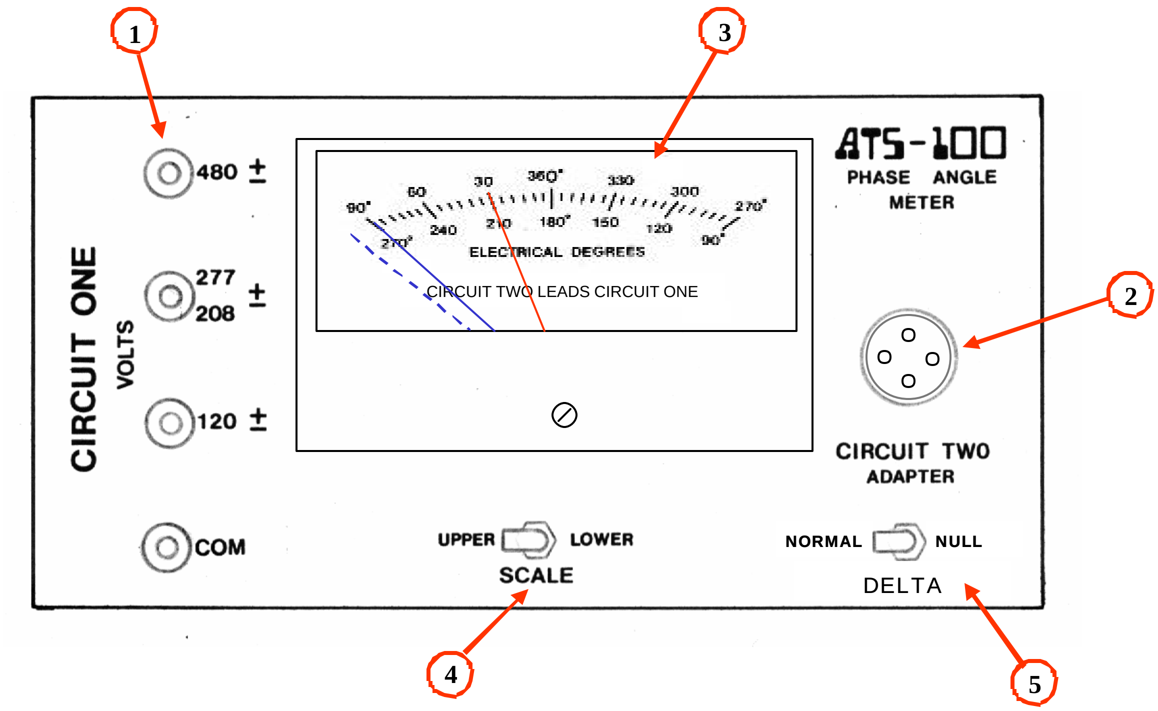
Used for voltage-voltage or voltage-current phase angle measurements.



ATS-100 Phase Angle Meter

Instrument Arrangement

Front Panel Layout



See Sheet 3 for Scale Interpretation Instructions and Sheet 4 for Condensed Operating Instructions.

1. CIRCUIT ONE - Reference Voltage Input. Input ranges 120 / 208-240 / 480 with respect to Common (COM).

2. CIRCUIT TWO - Adapter Input Receptacle which accepts the following adapters:

   Voltage Adapter - 120, 208 - 240, and 480 VAC adapters are available.

   Low Current Adapter - TPI Model 254 (10 mA to 60 amps). Recommended for current measurements on the secondary of 5 amp Instrument Current Transformers (CT's).

   High Current Adapter - TPI Model 256 (0 to 400 amps). For direct phase angle measurement on motors and other loads to 400 amperes.

   Fiber Optic Adapter - ATS Model 110 Receiver. For use with the ATS Model 111 Fiber Optic Transmitter which permits direct phase angle measurement on distribution power lines to 34.5 kV up to 400 amps.

3. ANALOG METER - Displays the number of electrical degrees which CIRCUIT TWO *leads* CIRCUIT ONE. Two scales, 0 - 360 degrees in four quadrants, five degrees / division.

4. SCALE SWITCH - Selects the UPPER (90^o - 360^o / 0 - 270^o) meter scale, or the LOWER (270^o - 180^o - 90^o) meter scale.

5. DELTA NULL SWITCH - Used to simplify voltage-current phase angle measurement on Delta Systems. On a Delta System, at unity power factor, there is a 30^o phase shift between the phase voltage and the line current. Holding this momentary-action switch in the NULL position will automatically compensate for this phase shift. (Switch is spring return to the NORMAL position.)

ATS-100 Phase Angle Meter
Scale Interpretation

Measurement Standards

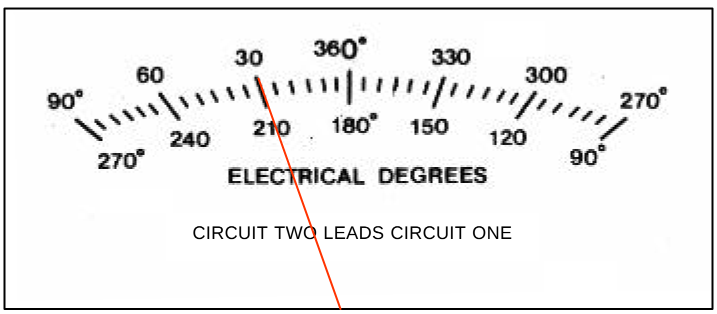
Phase Angle Meters are manufactured using two different standards:

1) Showing the number of degrees that Circuit Two *leads* Circuit One.

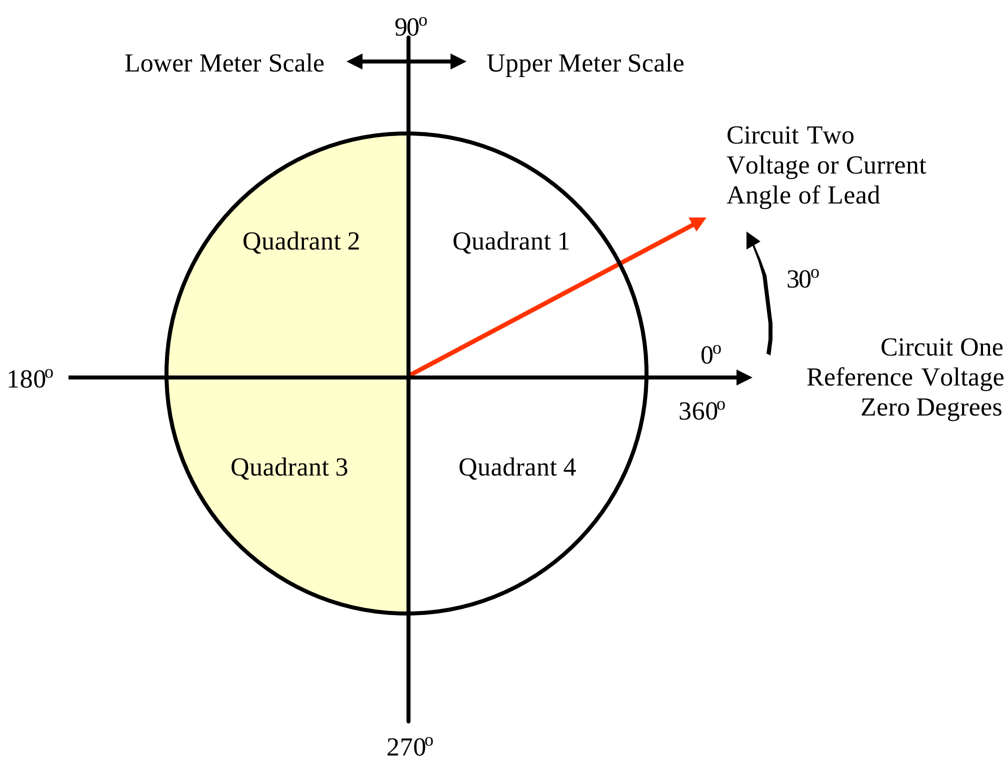
2) Showing the number of degrees that Circuit Two *lags* Circuit One.

Because Phasors (electrical vectors) are always analyzed with a Counter Clockwise Rotation (CCW), the first standard, showing the number of degrees Circuit Two *leads* Circuit One, is more consistent with this theory and is employed on the ATS-100 instrument. The second standard, showing degrees of *lag*, is sometimes preferred when power factor measurements only are being made as the angle of lag for single-phase analysis will always be in the fourth quadrant.

The ATS-100 instrument displays the 360^o electrical degree measurement two quadrants at a time as determined by the position of the SCALE SWITCH (see previous page). The UPPER SCALE switch position is for Quadrants 1 & 4 with the number of degrees being read from the Upper 90^o - 360^o / 0^o- 270^o meter scale. The LOWER SCALE switch position is for Quadrants 2 & 3 and the number of degrees is read from the lower 270^o - 180^o - 90^o meter scale. When making measurements, place the SCALE SWITCH in the position that gives an upscale reading.



Upper scale meter reading corresponds to red phasor position illustrated below.



ATS-100 Phase Angle Meter

Condensed Operating Instructions

Refer to Illustration on Sheet 2

Making Voltage-Voltage Phase Angle Measurements

1) Apply the reference potential to the appropriate CIRCUIT ONE input banana jacks. Use the red lead for the polarity (±) connection and the black lead for the common (COM) connection. (With voltage applied, the meter hand will move upscale from the position indicated by the dashed blue line to the 90° / 270° mark shown by the solid blue line.)

2) Connect the appropriate voltage adapter with potential leads to the CIRCUIT TWO adapter input. Use the red lead for the polarity connection and the black lead for the non-polarity connection.

3) Place the SCALE SWITCH in the position that provides an upscale reading and read the indicated phase angle from the appropriate scale. For example: if an upscale reading is obtained with the SCALE SWITCH in the UPPER position the reading indicated by the red hand would be read as 30 degrees; if an upscale reading is obtained with the SCALE SWITCH in the LOWER position, the reading would be taken from the LOWER scale, which for this example, would be read as 210 degrees. The meter scale indicates the number of electrical degrees that the potential applied to CIRCUIT TWO *leads* the reference voltage applied to CIRCUIT ONE.1)

   Note: All voltage-voltage phase angle measurements are made with the momentary-action DELTA NULL SWITCH in the NORMAL position.

   See Sheet 6 for information on determining the system phase rotation and Sheets 7 & 8 for details on making measurements and constructing a system phasor diagram.

Making Voltage-Current Phase Angle Measurements

1) Apply the reference potential to the appropriate CIRCUIT ONE input banana jacks. Use the red lead for the polarity (±) connection and the black lead for the common (COM) connection.

2) Use the TPI A254 Low Current Adapter when making measurements on the 5 amp secondary side of instrument Current Transformers (CT's), on small loads under 60 amperes (600 volts or less), or for analyzing small motor starting where the Locked Rotor Amps (LRA) is less than 60 amps. The TPI A256 Clamp Adapter should be used (600 volts or less) on for loads up to 400 amps, motor loads where the Full Load Amps (FLA) does not exceed 400 amps, or for analyzing motor starts where the LRA does not exceed 400 amps.

   Connect the appropriate current adapter to the CIRCUIT TWO adapter input. A special identification circuit in the adapter plug "tells" the instrument which adapter is being used.

   Place the Current Adapter Selector Switch in the AC position and place the adapter around the current-carrying conductor . The side of the adapter with the writing and switch is the polarity side (±) and must be placed toward the power source or toward the current transformer polarity mark when measuring on the secondary side of a CT.

3) Place the SCALE SWITCH in the position that provides an upscale reading. The meter scale indicates the number of electrical degrees that the current applied to CIRCUIT TWO *leads* the reference voltage applied to CIRCUIT ONE.

4) The DELTA NULL SWITCH can be placed in the NULL position to compensate for the 30° phase shift that exists between the phase voltage and the line current in a Delta System. Leave the NULL switch in the NORMAL position for making Voltage-Current phase angle measurements on a WYE System.

   See Sheet 6 for information on determining the system phase rotation and Sheets 7 & 8 for details on making measurements and constructing a system phasor diagram.

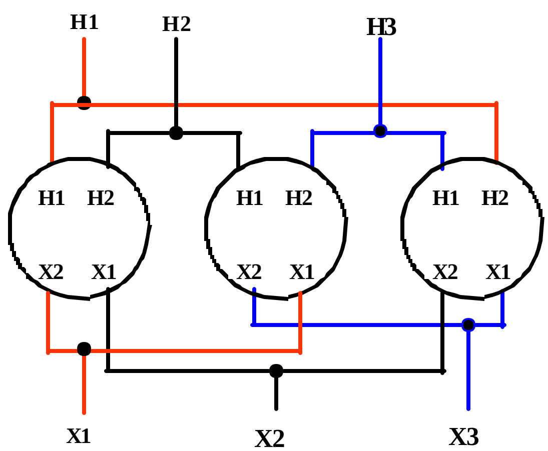
Transformer Bank
Connections and Phasor Diagrams

Paralleling Considerations

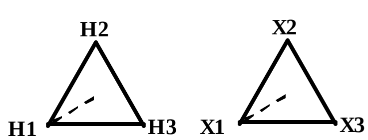
The following connection diagrams illustrate how a change in the connection of three single-phase transformers in a three-phase bank will change the phasor diagram for the bank. This condition holds true for all bank configurations; only the Delta-Delta connection with additive polarity transformers is shown here.

In order for the transformer banks to be paralleled, the banks must be connected so that the same phasor diagrams results. Prior to interconnection of a three-phase bank with an existing bank or an existing system (bus or line) the proper connection is verified by a process known as "phasing-out". This can be accomplished on Low Voltage Systems (below 600 volts) using a voltmeter. On Medium Voltage Systems a Phase Angle Meter can be used to compare the 120 volt secondaries of Instrument Potential Transformers (PT's), or insulated Phase Sticks, which incorporate a meter and voltage dropping resistors, can be employed. Lamp-type high voltage testers should not be used for phasing-out because a small angular difference between the systems, such as exists with a 30^{o} phase shift, may not produce enough voltage to illuminate the lamp.

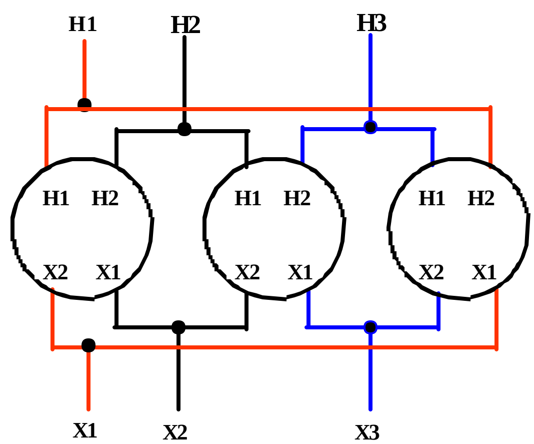
Angular Displacement 0^{o}



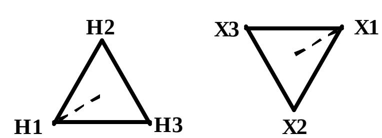
The connection above produces the standard phase relationship illustrated below. This connection would be used internally on a three-phase transformer but would not normally be used for connecting three single-phase transformers where a standard phasor relationship is not required.



Angular Displacement 180^{o}

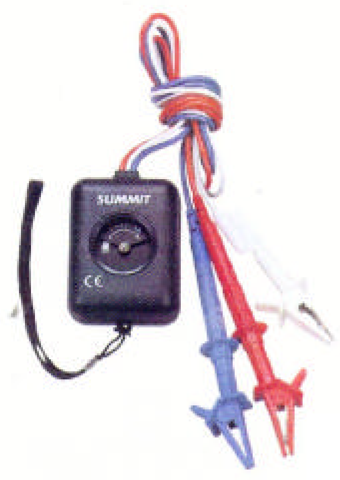


The connection above produces the non-standard phase relationship illustrated below. This configuration is most common on distribution lines because of its simplicity (no crossed conductors) and will parallel with other banks provided they are wired exactly the same. This bank will not parallel with the one shown at the left.



The dashed lines in the symbols above indicate the phase relationship between the primary and secondary of a particular connection configuration. For the connection shown above left, which has a 0^{o} angular displacement between the primary and the secondary, the position of the dashed reference is identical. In the configuration shown above right, the position of the dashed lines indicate a 180^{o} phase shift between the primary and the secondary.

Summit SPD480 Phase Rotation Indicator



Determining Rotation

The rotation of a three-phase system or motor can be changed by reversing any two of the three leads.

An easy way to determine the phase rotation of a three-phase system is to use a phase rotation indicator such as the one shown at the left. The unit pictured is an induction–disk instrument that is essentially a three-phase induction motor. The lead identification is: A Phase - Red, B-Phase - Blue, C Phase - White. When connected to a system with ABC rotation the disk rotates clockwise. If the system rotation is ACB the disk rotates counter-clockwise.

Phase rotation indicators which use lamps to show the phase sequence are also available.

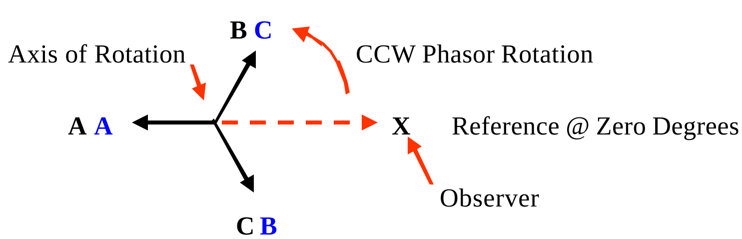
A motor rotation indicator is also made which can be used to determine the phase sequence required to produce the desired motor rotation. The instrument is connected to the motor leads prior to wiring and then the motor shaft is turned in the desired direction of rotation; the meter will show the necessary phase sequence to be applied. (When the motor shaft is turned, the motor acts as an induction generator.)

Standard Phasor Rotation

While the rotation of electric motors is referred to as either clockwise or counter-clockwise, for the purpose of analyzing three-phase systems, the rotation of electrical phasors is always shown as counter-clockwise (CCW) with the reference phasor drawn horizontally pointing to the right. (Phasors are electrical vectors which show magnitude and direction.) If the observer stands at Point X in the drawing below, the phasors can be imagined as turning past the observer in a CCW direction.

- To illustrate an ABC system rotation the phasors are labeled so as to appear in an ABC sequence.
- To show reversed system rotation the phasors are labeled so that the phase labels appear in a ACB sequence.

Assigning the labels A, B, and C is actually somewhat arbitrary; all one really knows is the rotation sequence. The A, B, C labels are usually initially applied at the source transformer or facility main disconnect and then follow the conductors through the system. The National Electrical Code reference on the subject is shown below.



Wye Phasor Diagram

Black letters show ABC rotation.
Blue letters show ACB rotation

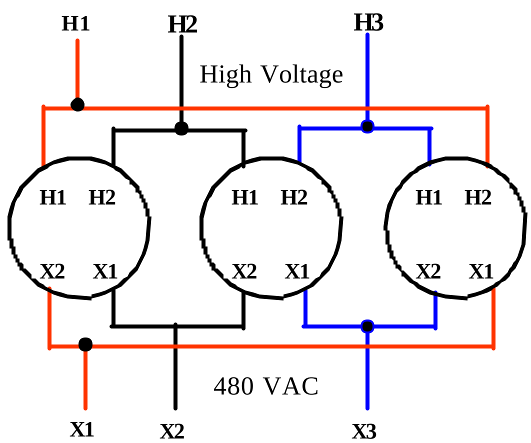
Imagine standing at point X and watching the phasors rotate past. Wait until A goes past and then note the following order.

2002 NEC Code Reference: ARTICLE 408 Switchboards and Panelboards. 408.3 Support and Arrangement of Busbars and Conductors. 408.3(E) Phase Arrangement. The phase arrangement on 3-phase buses shall be A, B, C from front to back, top to bottom, or left to right, as viewed from the front of the switchboard or panelboard. The B phase shall be that phase having the higher voltage to ground on 3-phase, 4-wire, delta connected systems. Other busbar arrangements shall be permitted for additions the existing installations and shall be marked.

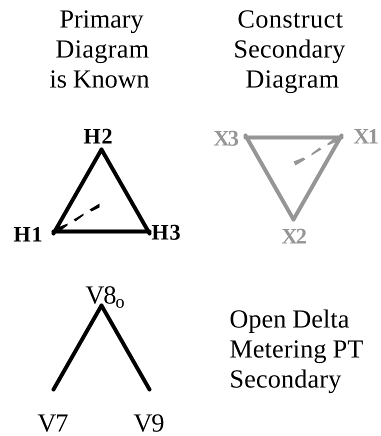
Sample Phase Angle Measurement Problem

Assume it is desired to measure the phase angles that exist on the secondary of the transformer bank connected in the manner shown below and then to construct the secondary phasor diagram from the measurements. (In this case we already know the answer based on the phasor diagram with the angular displacement of 180° shown on the Sheet 5.) Assume, also, that high-side bus potential transformers (not shown) are available for supplying a reference potential for the phase angle meter, and that the primary phasor diagram and the secondary lead designations (X1, X2, X3) are known.

Bank Connection Diagram



Phasor Diagram



Phase Angle Meter Connections

The reference phasor is always drawn horizontally to the right; selecting the primary H1 to H3 voltage for a meter reference will result in an applied voltage that is in the same direction. Because the primary is high voltage, and the meter Circuit One input voltage is 120 VAC, the high voltage bus potential transformers (PTs) are used to supply the 120 VAC for the meter reference input. The PT secondary V7 to V9 voltage will be in the same direction as the primary H1 to H3 voltage.

- Connect the PT secondary V7 to V9 voltage to Circuit One of the phase angle meter. The PT secondary V7 is connected to the phase angle meter Circuit One red ± lead. The PT V9 is connected to the Circuit One black lead.

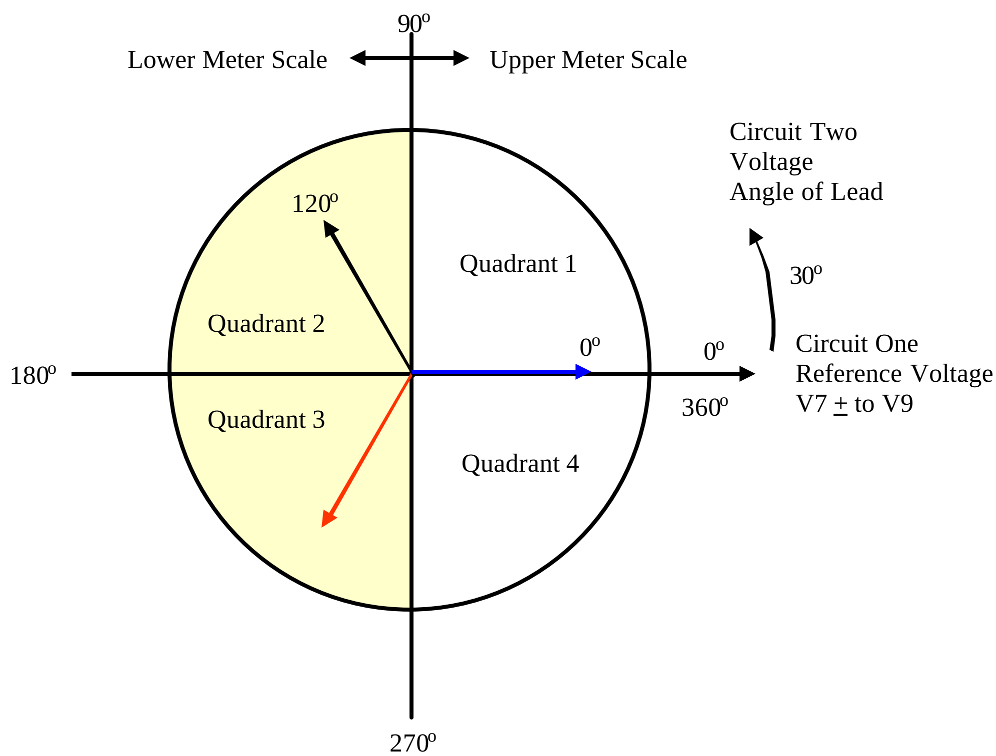
- Using the 480 Volt Circuit Two Adapter, sequentially connect the transformer bank secondary potentials X1, X2, and X3 to the phase angle meter Circuit Two input leads as shown in the following table. The phase angle degree measurement that would result for each input is recorded in the Measured Angle Degrees column of the table.

Measurement Results		
Circuit Two Lead Connections		**Measured Angle Degrees**
Red Lead ±	**Black Lead**	
X1	X2	240
X2	X3	120
X3	X1	0

See Sheet 8 for phasor diagram construction based on the above measurements.

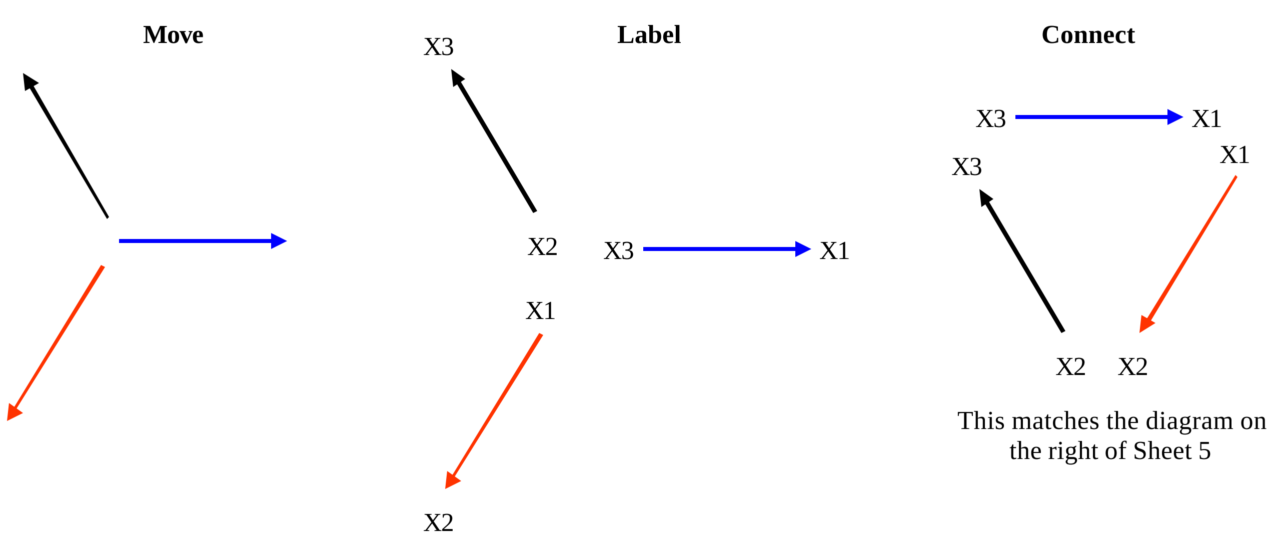
Phasor Diagram
Construction

Plot of the phase angle measurements made on Sheet 7



Construct the phasor diagram in the space below in accordance with the following rules:

- Move each of the phasors to the space below without changing its orientation.
- Label each phasor with the X designation used for the measurement. The tail of each arrow is the polarity ± end of the phasor.
- Connect the phasors together: X1 to X1, X2 to X2, and X3 to X3.



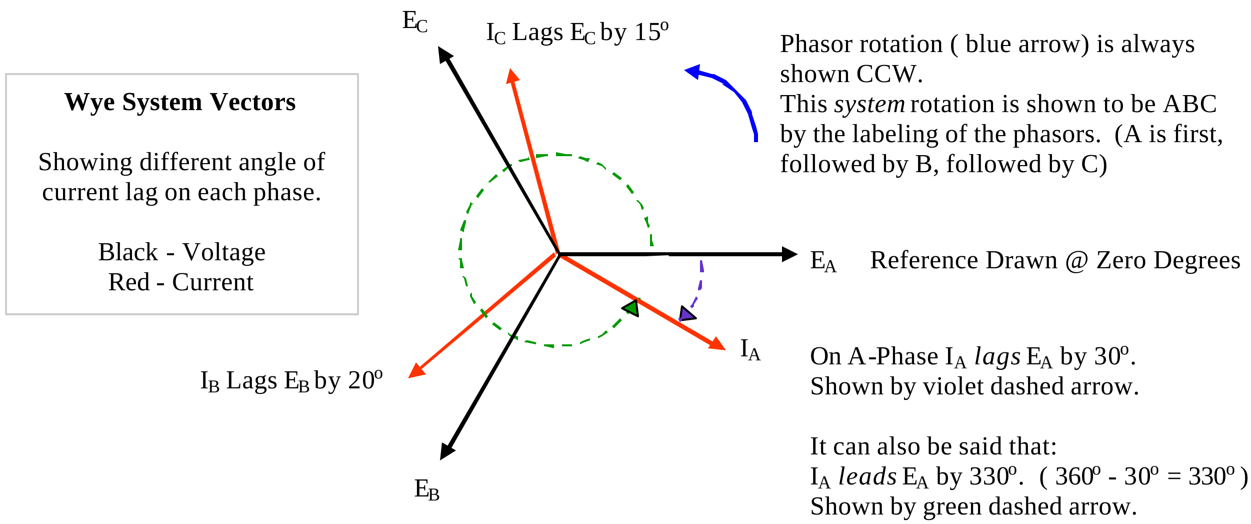
This matches the diagram on the right of Sheet 5

Phase Angle Measurement
Voltage-Current

Purpose

There are two reasons for making electrical system voltage-current phase angle measurements.

1. To determine the system power factor for system load studies and power factor correction studies.
2. To verify that power metering equipment and protective relays are properly connected.



1. Phase Angle Measurement for Power Factor Determination

In the ideal AC electrical system the voltage and current are in phase. This condition only occurs on systems where all of the load is resistive, such as electric heat, incandescent lighting, or fluorescent lighting with power factor corrected ballasts. Electrical utilization equipment such as motors and welders have a considerable amount of inductance and the inductive reactance (X_L which is measured in ohms) causes the circuit current to lag the applied voltage. The actual amount, or number of degrees of lag, depends on the ratio of the Inductive Reactance (X_L) in ohms to the ohmic value of Resistance (R) of the system.

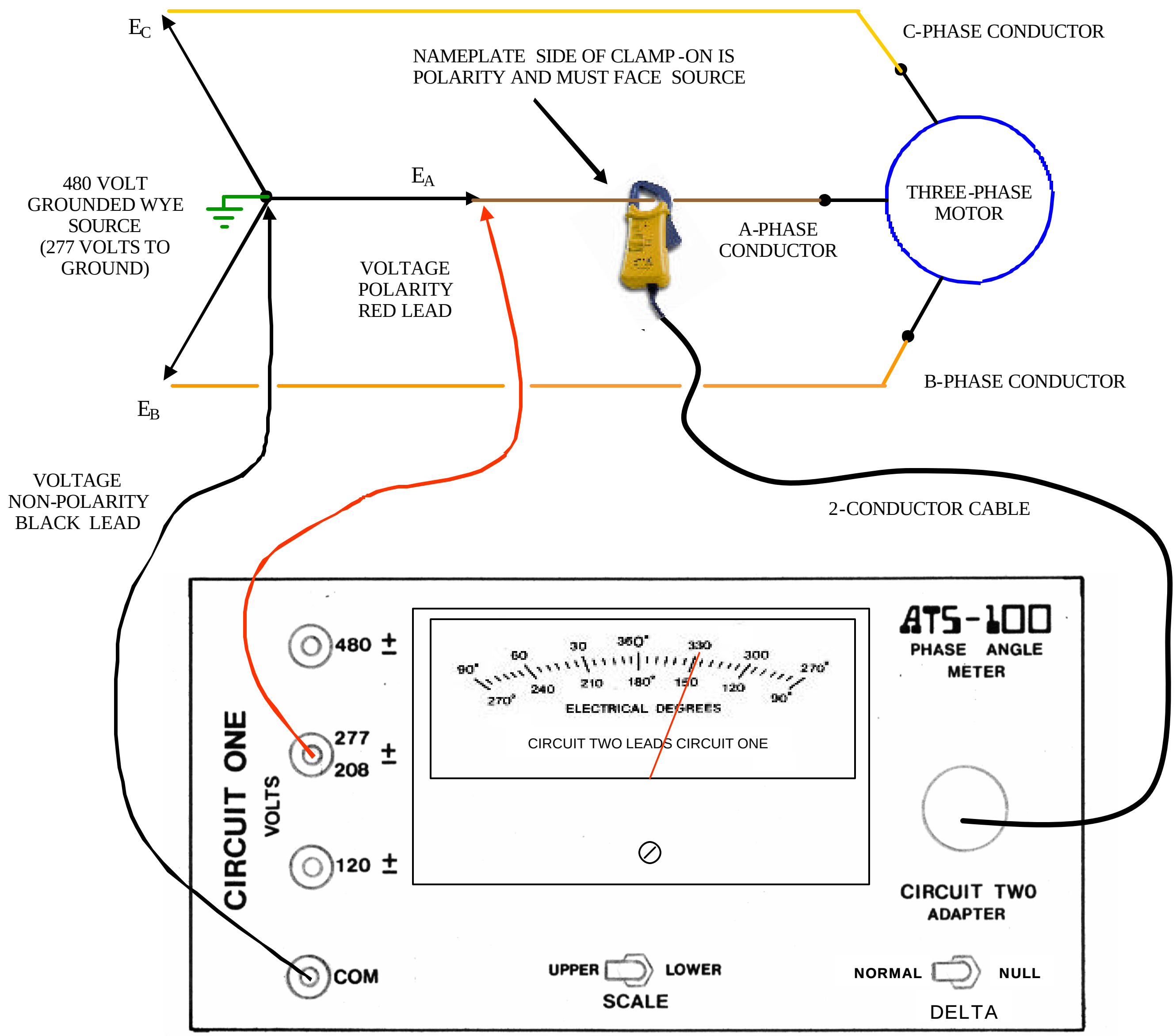
The system power factor is the cosine of the phase angle between the system voltage and the system current expressed as a percent. For example, if the current is determined by measurement to lag the applied voltage by 30 degrees, as shown for A-Phase in the example above, the power factor of the system would be 86.6 percent. This is determined by finding the cosine of 30 degrees which is 0.866 (you can use either a Trigonometry Table or an Engineering Calculator for this) and multiplying the cosine of the angle by 100 to obtain the percent power factor.

Once the system power factor is known, power factor correction, if desired, can be applied to the system using power factor correction capacitors or by using synchronous motors, either of which can supply leading Volt Amperes Reactive (VARs) to the system to compensate for the lagging power factor. Most electric utilities charge a penalty for poor system power factor, so keeping the power factor above the required minimum value will result in a lower utility bill and will also improve the voltage drop on the system.

When using the ATS-100 Phase Angle Meter, or similar instrument, the power factor is measured one-phase-at-a-time. On a three-phase system the load will rarely be perfectly balanced, so the power factor on each phase may differ because of the unbalance of the single-phase loads. If all of the load was due to three-phase motors the power factor on each phase would be the same, at least in theory. However, in practice, there is always some voltage imbalance between phases which will result in an even greater percentage of current imbalance.

Phase Angle Measurement
Wye System

Instrument Connections



Measurement Analysis

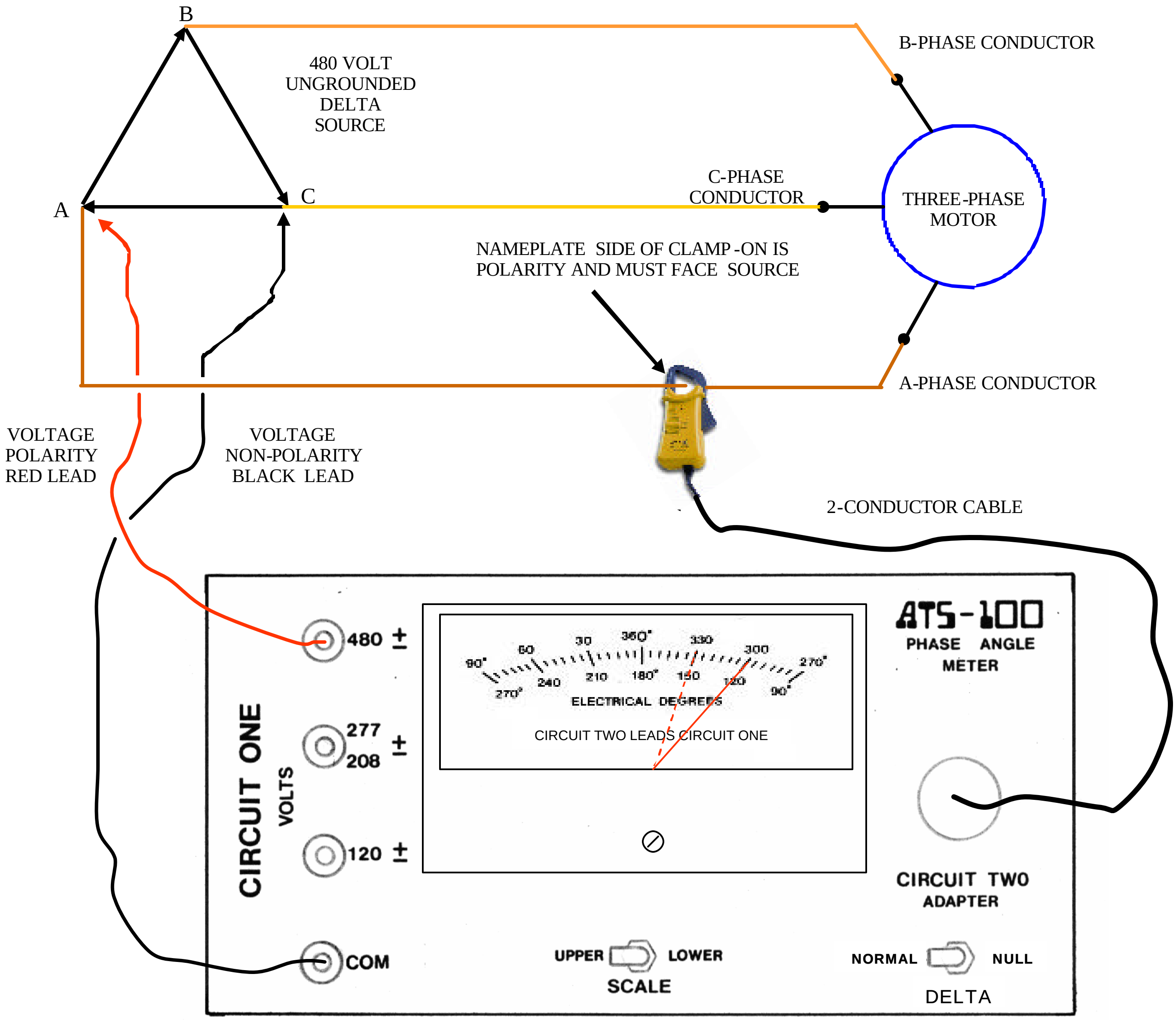
Voltage-Current phase angle measurement is easily accomplished on a WYE system because, on any given phase, the phase current and the phase-to-ground voltage are in-phase at unity power factor. The voltage-current phase angle measurement may be taken directly from the phase angle meter. See the following page for a description of the requirements for making voltage-current phase angle measurements on a DELTA system.

With all phase angle measurements, whether they be voltage-voltage or voltage-current, lead polarity is critical. Polarity for the voltage leads and current probe for the ATS-100 are shown above. Check the instruction manual for the instrument you are using.

Some phase angle meters, including the ATS-100, measure the angle of *lead* between the reference voltage which is applied to CIRCUIT ONE of the meter and the current which is applied to CIRCUIT TWO of the meter. When a meter using this standard is employed, the measurement reading is subtracted from 360^o to give the angle of lag. In the example on the preceding page, the 30^o angle of lag would be read on the upper scale of this meter as 330^o lead.

Phase Angle Measurement
Ungrounded Delta System - Sheet 1 of 2

Instrument Connections



Measurement Analysis

On a DELTA system, there is an inherent 30º phase shift (at unity power factor) between the line (phase) voltage and the line current which must be accounted for. This is because the line current on a DELTA system is the vector sum of two separate phase currents (see the DELTA system phasor diagram on Sheet 1of the AC Systems Article).

In order to obtain a correct reading, voltage and current of the proper phase and polarity must be applied to the instrument. See the following page, Sheet 12, for information on phase identification and meter connections.

The diagram above shows the proper connections for measuring the phase angle between the A-Phase Current and the A-Phase Voltage (Line E_{C-A}). Assume the motor is running at a 30º lag (86% Power Factor). Because the ATS-100 meter indicates the number of degrees that Circuit Two *leads* Circuit One, the 30º lag will be read as 330º lead. However, because of the inherent 30º lag on the DELTA system, the meter will actually read 300º lead as shown by the solid red hand. The 30º difference must be added to the 300º to obtain the correct 330º reading. On the ATS-100, holding the momentary action DELTA switch in the NULL position will automatically adjust the reading by 30º and the meter hand will register the 330º reading as shown by the dashed red line.

Phase Angle Measurement
Ungrounded Delta System - Sheet 2 of 2

Phase Identification

Phase identification for correct instrument connection on a DELTA system is most easily accomplished using a phase rotation meter (See Sheet 6). Simply connect a rotation meter to the phase conductors so that a clockwise ABC rotation is indicated on the meter, then label the phases to match the A, B, C, labeling on the rotation meter leads. (Remember, even though the rotation meter shows a clockwise rotation, for the purpose of system analysis, all phasors are assumed to have a Counter-Clockwise Rotation.)

The table below shows the voltage and current connections required for making phase angle measurements on a DELTA system.

Current and Voltage Polarity for Delta System Phase Angle Measurement

Current Probe on Phase (Polarity Toward Source)	Potential Lead Connections Red (+) Polarity	Black (COM)
A	**A**	**C**
B	**B**	**A**
C	**C**	**B**