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In This Issue

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ELECTRICAL NETWORKS FOR ZERO SUPPRESSION

THE CONVENTIONAL method of suppressing a portion of the scale range of electrical instruments by control spring rotation generally results in instrument characteristics which are acceptable in return for improved scale readability at the point of greatest interest. Suppressions greater than two scale lengths, however, tend to develop undesirable characteristics such as spring fatigue with the result that the scale calibration is not permanently preserved.

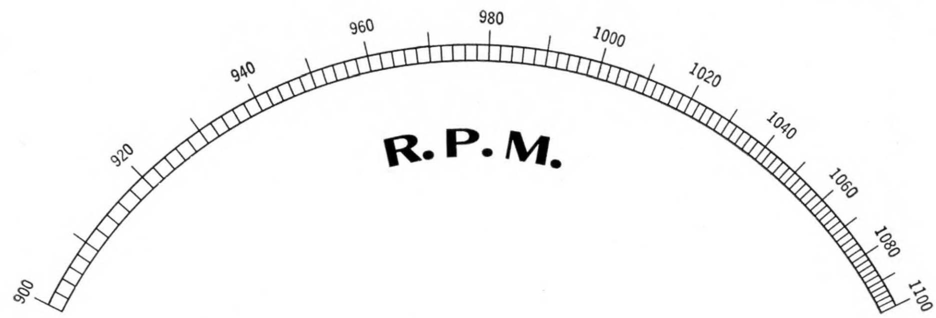


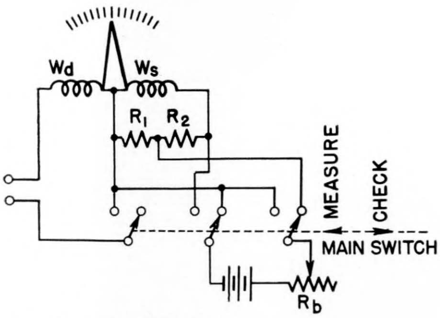
Figure 1—Conventional Scale—Mechanical Suppression

Another effect of zero suppression by mechanical means using conventional mechanisms, is the scale distortion shown in Figure 1. This is due to expanding, by the suppression, the otherwise relatively minor lack of perfect flux uniformity in the gap. Since zero suppression is aimed at improved scale readability, its purpose is defeated if the divisions are seriously crowded at one end of the scale.

For these reasons mechanical suppression of more than two scale lengths is impracticable and must be abandoned in favor of an electrical method employing a differential network by which suppressions of four or five scale lengths may be readily accomplished without undesirable effects on the control springs or the scale distribution.

To provide adequate electrical suppression it is necessary that opposing or differential torques be produced without merging the battery and measuring circuits; otherwise resistance changes in the battery voltage compensation network would be reflected in the measuring circuit with consequent error in indication. The necessary differential torques are obtained by using a center tapped moving coil, one-half of the winding being the "suppression" winding, and the other half the "deflection" winding.

The former is made part of a resistance network capable of dividing the battery current between the suppression winding and a by-pass and inverting this current division without change in total network resistance. The regrouping of the network resistances is controlled by a switch. (See Figure 2)



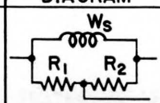
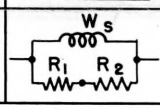
Wd Deflection Winding
Ws Suppression Winding
R1 And R2 Suppression Network Resistors
Rb Suppression Current Regulation

Figure 2—Schematic diagram for electrical zero suppression.

With the deflection winding disconnected, the battery current is adjusted by means of rheostat R_b until the instrument pointer reads exactly full scale. By reversing the battery polarity and re-grouping the network resistances, the current in the suppression winding is reversed and increased to the desired multiple of its former value, thus producing the desired amount of zero suppression torque without change in total battery current.

Since the battery load is insignificant with relation to battery capacity, the torques produced in the suppression winding will be strictly proportional to the resistance relationship within the network. This alone, therefore, determines the amount of suppression. Once the suppression is adjusted, the deflection winding of the moving coil is connected into its circuit and the instrument functions as a conventional instrument with zero suppression. Yet, it does possess the conventional zero corrector. Moreover, the amount of zero suppression can be re-checked at any time by moving the switch from the operating position back to the "CHECK" position. (See Figure 2.)

Figure 3 shows the suppression circuit arranged in the two fundamental positions of the control switch, reduced to its simplest form. It is necessary (a) to provide equal battery currents for both switch positions to eliminate the effect of the adjusting resistance R_b, (b) to shunt the suppressing current and reduce it to a full scale deflection of the pointer in the check position, and (c) to provide the correct current value in the suppression winding in the measuring position. W_s is the resistance of the suppression winding, R_1 and R_2 are the main elements of the resistance network. These requirements are satisfied when the resistance of $R_1 = W_s$ and when $R_2 = (n\text{-}1)\,R_1 = (n\text{-}1)\,W_s$ where n equals the number of scale lengths to be suppressed.

SWITCH POSITION	SCHEMATIC DIAGRAM	RESISTANCE RELATIONSHIP
CHECK		$W_s + R_2 = nR_1$
MEASURE		$R_1 + R_2 = nW_s$

From The Two Resistance Relationships Follows $R_2 = R_1\,(n-1)$

Figure 3—Simplified checking and measuring circuits.

Let the problem be that of measuring speeds from 900 to 1100 rpm on one scale length. This means $n = 4.5$. Let either section of the moving coil by itself permit full scale pointer deflection at 1 milliampere. With R_2/R_1 adjusted to 3.5 and the switch in "CHECK" position, and with absolute resistance values in the network properly adjusted, there will be 1 milliampere in the suppression winding when the pointer reads full scale, and 4.5 milliamperes will be diverted through shunt R_1. The total battery current is 5.5 milliamperes. When the switch is moved into the operating position, the battery polarity is reversed; 4.5 MA is now flowing through the suppression winding, 1 milliampere is diverted through shunt $R_1 + R_2$ and the total battery current is still 5.5 milliamperes. This produces the desired scale range and the proper amount of suppression.

Figure *4* shows the scale of such an instrument. Comparison with Figure *1* shows that the scale of an electrically zero suppressed instrument is uniformly divided.

As shown in Figure *5*, the master switch is conveniently mounted in a separate box with binding posts for connection to the instrument proper, the circuit under test (for instance, a tachometer magneto) and the suppression current source with its regulating rheostat. In addition to the various operating positions and the "CHECK" position the switch carries an "OFF" position in which all circuits are disconnected.

In order to keep the physical complexities of the switch and network within practical limits, instruments with electrical suppression are produced with a maximum of four different suppressions, one of which may be, but need not be, zero, meaning

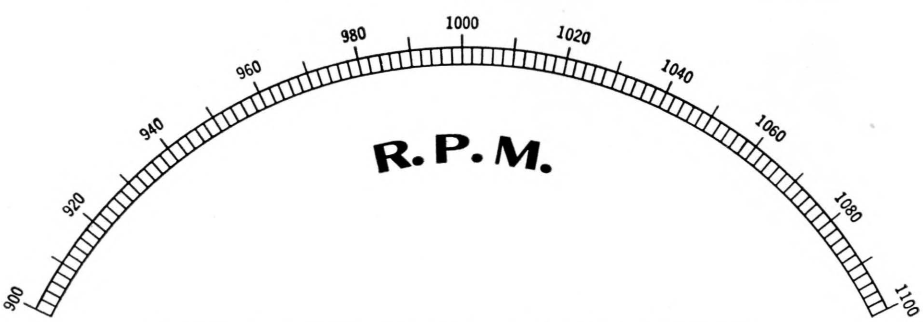


Figure 4—Conventional Scale—Electrically Suppressed.

that one range may start at 0 on the scale. For reasons of network adjustment to practical constants the maximum suppression offered is in the order of 4.5 scale lengths. The number of ranges per instrument may exceed the number of suppressions if several ranges share equal amounts of suppression.

Accuracy

The objective of zero suppression is the stretching of the scale for the sake of improved readability near the point of greatest interest. If such greater readability is achieved without sacrifice of accuracy, it may assist greatly in the use of the instrument.

For a 1% instrument arranged with mechanical zero suppression, it is a conservative practice to state its long term accuracy as 2%. In the case of electrical zero suppression the achievable accuracy can be estimated as follows:

Barring improper means of regulation, the suppression current can be adjusted to an accuracy determined by that of the basic (unsuppressed) instrument itself. If n is the number of scale lengths suppressed, any error in suppression current adjustment will translate itself into $\frac{n}{n + 1}$ times that error in suppression torque. If the accuracy of the basic instrument is 1% of full scale (of length "1"), the suppression accuracy will be $\frac{n\%}{n + 1}$ of full scale (of length "n + 1").

Figure 5—The Weston Model 273, multi-range instrument with external control box.

An actual reading made with the same instrument will again be accurate within 1% of the visible scale length. Set in relation to the stretched scale length this tolerance will seem reduced to $\frac{1\%}{n + 1}$ of full scale. In any event, the basic accuracy of the instrument is at least sustained in the process of electrical zero suppression, and this conservative statement is fully substantiated by instruments actually made and tested.

Electrical zero suppression has opened the way to range combinations not hitherto possible. In contrast to mechanical suppression which remains fixed, electrical suppression can be varied by suitable switching and network variations, with or without simultaneous change in the instrument range. Instruments of this type have been manufactured with multi-ranges of 0 to 2000 rpm with a scale span of 500 rpm per range, and 500 to 4000 rpm also with a scale span of 500 rpm per range. Other ranges can be readily made available as required.

—M. C. Kunz
—H. Berring

E. N.—No. 49

THE MEASUREMENT OF REACTIVE POWER - PART II
THREE-PHASE CIRCUITS

A THREE-PHASE circuit is a combination of circuits energized by electromotive forces which differ in phase by 120°. The two most common forms are, three-wire systems in which the source may be connected Y or Delta with three line wires available for the load, and four-wire systems which have, in addition to the three line wires, a neutral which is also connected to the load. If the neutral does not carry current the system may be treated as a three-phase three-wire system. If the neutral does carry current a special treatment must be made which will be described later.

The vector diagram of the three-phase three-wire system Figure 9 shows the three electromotive forces represented by V_{AO}, V_{BO} and V_{CO}, each positioned 120° from the other and becoming a maximum in the order named signifying counter clockwise rotation. The phase currents are represented by the vectors I_A, I_B and I_C, which are assumed to be lagging the associated EMF's by equal angles of ϕ degrees. When the electromotive forces are all equal and positioned with respect to each other as shown, the system is considered to be balanced for voltage. If the load circuit is such that the currents are equal in magnitude and displaced by equal angles with respect to the electromotive forces, the system is also balanced for current.

The measurement of active or reactive power in three-phase three- or four-wire circuits may be accomplished by several methods. In general, the method to be used will be determined by the circuit load conditions, that is, balanced or unbalanced current or voltage, etc.

The most common and preferred method for measuring active or reactive power in the three-phase three-wire system requires the use of two single element electrodynamometers or a two element instrument and is known as the "Two Wattmeter Method."

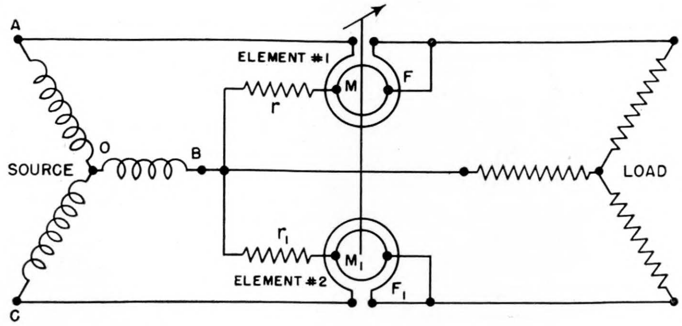


Figure 11—Schematic connections for a two-element wattmeter to a three-phase three-wire system.

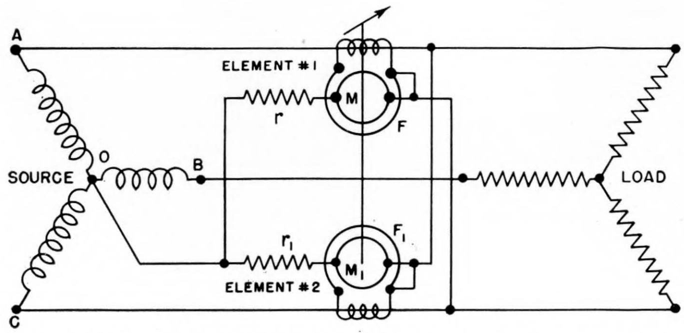


Figure 12—Schematic connections for a two-element varmeter to a three-phase three-wire system when the neutral is available. Current transformers are used.

Three-Phase Three-Wire Circuits

To measure active power, one element is connected with its current circuit in line *A* and its potential circuit connected from line *A* to *B*. The other element is connected with its current circuit in line *C* and its potential circuit connected from line *C* to *B*. These connections are shown schematically in Figure 11 and vectorially in Figures 9 and 10.

In a balanced system having a sinusoidal wave form the torque developed in element #1 is proportional to $V_{AB} I_A \cos (30 + \phi)$ and represented by the projection of I_A on V_{AB} marked *OD* for systems having lagging currents. For leading currents the torque developed in element #1 is proportional to $V_{AB} I_A \cos (30 - \phi)$. The torque developed in element #2 is proportional to $V_{CB} I_C \cos (30 - \phi)$ represented by the projection of I_C on V_{CB} marked *OE* for lagging currents and $V_{CB} I_C \cos (30 + \phi)$ for leading currents. The total power is proportional to the sum of these torques, that is,

$$V_{AB}\, I_A \cos (30 + \phi) + V_{CB}\, I_C \cos (30 - \phi)$$

which after assigning the numerical value for $\cos 30$, may be simplified to $VI\sqrt{3}\cos\phi$. where *V* represents line-to-line potential *AB* or *CB* and *I* the line current I_A or I_C.

Although the above equations are based on a balanced system having sinusoidal wave form they are derived from the well known two wattmeter method which is entirely independent of balance or wave form and true for systems connected in △, or in Y when no connection is made between neutrals of source and load*.

*The proof of this general statement may be found in technical books on the subject, such as "Principles of Alternating Currents" by R. R. Lawrence.

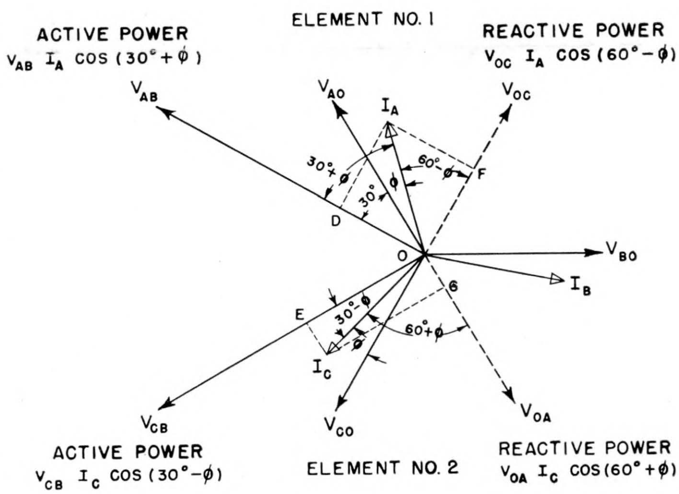


Figure 9—Angular relation between currents and potentials in a three-phase system, when currents lag potentials.

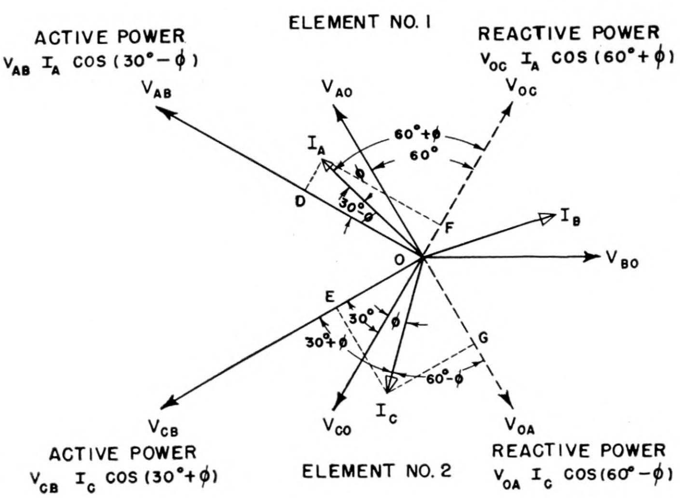


Figure 10—Angular relation between currents and potentials in a three-phase system, when currents lead potentials.

This method and basic instrument may be used to measure reactive power directly by selecting or constructing potentials displaced by 90 degrees from the potentials used to measure the active power.

To measure reactive power the potential connections to V_{AB} are shifted, so as to effect a 90 degree clockwise rotation to V_{oc} as shown in the vector diagram, Figure 9, and the torque developed in element #1 will be proportional to the component of I_A in phase with V_{OC} marked *OF* resulting in a positive or upscale indication proportional to $V_{OC} I_A \cos(60 - \phi)$ when I_A lags V_{AO} by ϕ degrees.

The potential connections for element #2 are also shifted from V_{CB} to V_{AO}, which is represented in the vector diagram, Figure 9, as a 90 degree clockwise rotation, resulting in a negative or downscale indication proportional to $V_{OA} I_C \cos(60 + \phi)$ when I_C lags V_{CO} by ϕ degrees. The indication of element #2 will be down-scale because the projection of I_C on V_{AO} marked O_G is actually 180 degrees from V_{AO}. This is opposite to the indication of element #1. The total reactive power will be the algebraic sum of these indications which for $\phi = O$, should be O.

When the currents lead their respective potentials by ϕ these relations are shown in vector diagram, Figure 10. Figure 12 shows the connections for the varmeter when the neutral is available and Figure 13, the connections to provide an artificial neutral when the true neutral is not available. In constructing the artificial neutral, r_2 is adjusted equal to either r plus its movable coil or to r_1 plus its movable coil since they are both equal.

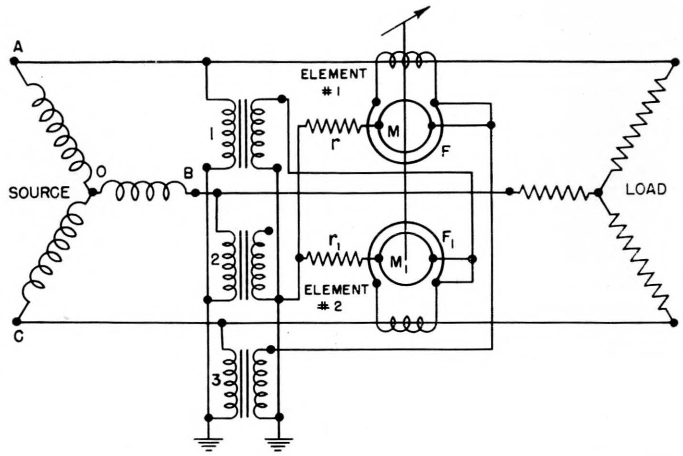


Figure 14—Schematic connections for a two-element varmeter to a three-phase three-wire system using potential and current transformers.

Figure 14 shows the connections of the varmeter when potential transformers are needed because of high line potentials. As will be evident from the diagram the potential transformer #2 may be omitted if not used for other instruments.

In transferring between line potentials and phase potentials allowance must be made for the fact that the line potential is $\sqrt{3}$ times the phase potential. A wattmeter calibrated for 1000 watts full scale and adjusted for a three-phase, three-wire circuit using line connections for its potential circuit, if connected to measure Vars by shifting its potential connections to phase connection, will have its potential reduced by $1/\sqrt{3}$. The angular deflection of its movable coil, and therefore its indication, will be reduced by $1/\sqrt{3}$ for the same power supplied to the load, and the full scale value will become $1000\sqrt{3}$ or 1730 Vars.

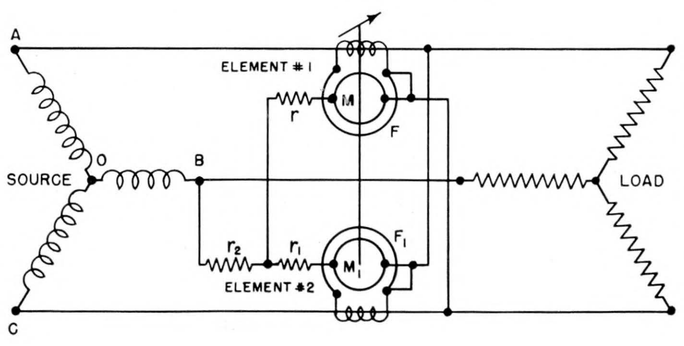


Figure 13—Schematic connections for a two-element varmeter to a three-phase three-wire system when the neutral is not available. Current transformers are used.

When using a two element electrodynamometer which has been adjusted and calibrated to measure watts for a three-phase three-wire system each element alone and both together should indicate as shown in Table 1.

The reading on the watt scale will be equal to the total volt-amperes of the load, $VI\sqrt{3}$ where V is the line potential and I the line current, times the factor in Table I. The indications will be up-scale (+) or down-scale (—) as shown.

The table shows that when measuring active power, the total deflection is always positive or in the up-scale direction and when measuring reactive power the total deflection is positive for lagging phase angle and negative for leading phase angle according to usual conventions. If a positive deflection for leading phase angle is desired, when measuring reactive power, each element should be reversed. This is often conveniently carried out by reversing the connections to the current circuit.

Current transformers are shown so that the movable and stationary coils may be connected together to avoid electrostatic effects.

A very convenient and simple method is to use the so-called auto-transformer in the potential

TABLE I
THREE-PHASE THREE-WIRE CIRCUITS
POTENTIALS AND CURRENTS BALANCED
TWO ELEMENT INSTRUMENT

Ø Deg.	Cos Ø or Power Factor	Lagging Ø Element #1	Lagging Ø Element #2	Lagging Ø Total	Leading Ø Element #1	Leading Ø Element #2	Leading Ø Total
Connected to Measure Watts (See Figure 11)							
0	1.00	(+) .50	(+) .50	(+) 1.00	(+) .50	(+) .50	(+) 1.00
30	.86	(+) .29	(+) .58	(+) .87	(+) .58	(+) .29	(+) .87
60	.50	0	(+) .50	(+) .50	(+) .50	0	(+) .50
90	0	(−) .29	(+) .29	0	(+) .29	(−) .29	0
Connected to Measure Vars (See Figures 12 and 13)							
Reading Watt Scale as Vars. Multiply by $\sqrt{3}$ for True Vars							
0	1.00	(+) .17	(−) .17	0	(+) .17	(−) .17	0
30	.86	(+) .29	0	(+) .29	0	(−) .29	(−) .29
60	.50	(+) .33	(+) .17	(+) .50	(−) .17	(−) .33	(−) .50
90	0	(+) .29	(+) .29	(+) .58	(−) .29	(−) .29	(−) .58

circuit to shift the phase and correct for the change in potential The auto-transformer consists of two branches tapped and connected as shown in Figure 15.

Considering the line potentials *AB, BC, CA* as representing an equilateral triangle, the auto-transformer when connected as in Figure 15 also forms an equilateral triangle as shown in Figure 16. The extensions of B_1A_1 and B_1C_1 as represented by A_1G and C_1N respectively are used to increase the potential applied to to the varmeter. To measure vars it is necessary to produce a potential in-phase with *OC* and equal to *AB* for element #1 and a potential in-phase with *OA* and equal to *BC* for element #2. From the geometry of the figure, *DN* is parallel to OC_1, and therefore in-phase with it. By the extension C_1N, the value of *DN* is made equal to A_1B_1.

The tap *D* is midway from B_1 to *G* and top *E* is midway from B_1 to *N*.

$$\frac{DN}{B_1N} = \cos \alpha = \cos 30^\circ = \frac{1}{2}\sqrt{3}$$

But $DN = B_1C_1 = B_1A_1$ by construction.

Then,

$$\frac{B_1C_1}{B_1N} = \frac{1}{2}\sqrt{3} = 0.866$$

Therefore,

$B_1C_1 = 0.866\ B_1N$ or $B_1N = 1.153\ B_1C_1$

If the complete branch B_1N is 100%,

Section $B_1E = 50\%$

Section $B_1C_1 = 86.6\%$

Likewise in Branch B_1G,

Section $B_1D = 50\%$

Section $B_1A_1 = 86.6\%$

This method is most satisfactory as it supplies not only a potential having the proper phase but also of the proper magnitude. Therefore, the instrument is adjusted exactly as a wattmeter and may then be connected as in Figure 11 for watts and Figure 15 for vars. A single instrument may thus be used with a four-pole double-throw switch to measure either active or reactive power.

This method is dependent on the potentials being balanced, but is independent of the current unbalance.

Where a three-phase three-wire system is completely balanced, the watts or vars may be measured by means of a single element instrument. The active power in watts may be measured in one phase and the reading multiplied by three or the scale calibrated in terms of total power when connected as shown in Figure 17. The reactive power of such a circuit in vars may also

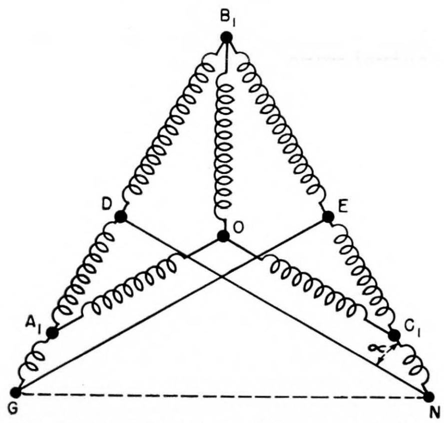


Figure 16—Relation of potentials in a phase shifting reactor for use on three-phase three-wire systems.

be measured with a single element instrument by selecting a potential in quadrature with *OB* which as shown in Figure 18 is *AC*. When using this connection, it should be recognized that potential *AC* is $\sqrt{3}$ times potential *OB* and proper allowance should be made in the instrument adjustment or indication.

An extra resistance may be arranged with a double-pole double-throw switch so that a single instrument adjustment and scale may be used for either watts or vars.

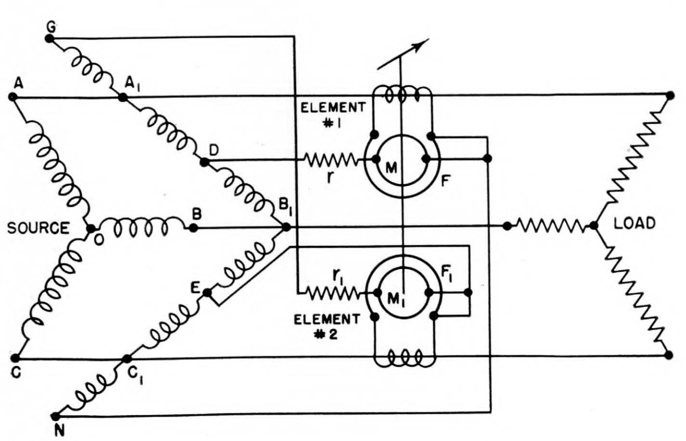


Figure 15—Schematic connections for a two-element varmeter to a three-phase three-wire system using a phase shifting reactor and current transformers.

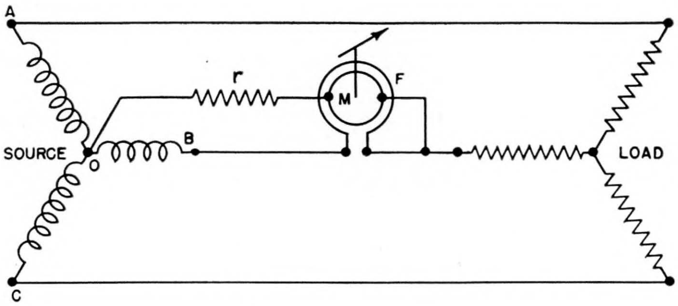


Figure 17—Schematic connections for a single-element wattmeter to a balanced three-phase three-wire system.

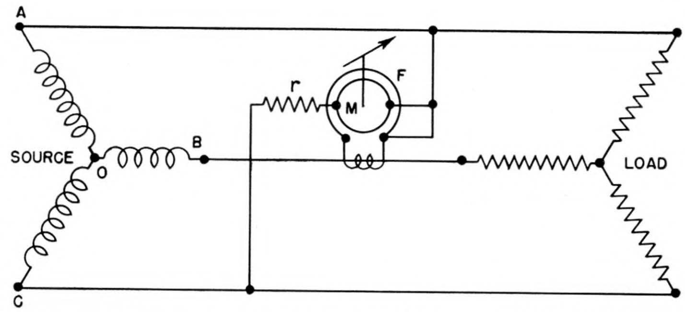


Figure 18—Schematic connections for a single-element varmeter to a balanced three-phase three-wire system. A current transformer being used.

Three-Phase Four-Wire Circuits

Where the neutral is used and the wire connecting to it carries current, the measurements of active or reactive power must take into account the current in the neutral wire.

A modified form of the two-element electrodynamometer, called the 2½ element electrodynamometer is quite commonly used, in which the current of the third wire is introduced into each element by dividing the field coils. Figure 19 shows the connections for using this instrument to measure the active power.

The vector diagram, Figure 20, shows that the total torque developed in element #1 is proportional to the algebraic sum of the two torques, $V_{AO}I_A$ *Cos* ϕ *and* V_{AO} $(-I_B)$ *Cos* $(60 - \phi)$. Likewise element #2 will have a total torque proportional to the algebraic sum of the two torques $V_{CO}I_C$ *Cos* ϕ and V_{CO} $(-I_B)$ *Cos* $(60 + \phi)$.

$V_{AO}I_A$ *cos* ϕ represents the active power in phase *A*. $V_{CO}I_C$ *cos* ϕ represents the active power in phase *C*, and V_{AO} $(-I_B)$ cos $(60 - \phi)$ added to V_{CO} $(-I_B)$ *cos* $(60 + \phi)$ results in the equivalent to $V_{BO}I_B$ *cos* ϕ which represents the power in phase B. The sum therefore represents the total power in the circuit.

To measure reactive power, the potential connections are shifted from V_{AO}, and V_{CO} to V_{BC} and V_{AB} respectively, so as to effect a 90 degree clockwise rotation when referred to the vector diagram, Figure 20. The connections for a 2½ element instrument to measure the reactive power are shown in Figure 21. It will be observed that in making this transposition of potential connections, the potentials applied to the instrument are increased by $\sqrt{3}$ and must be taken care of in the series resistance, or the range of full scale value will be reduced by this factor. This is opposite from the three-phase three-wire instrument.

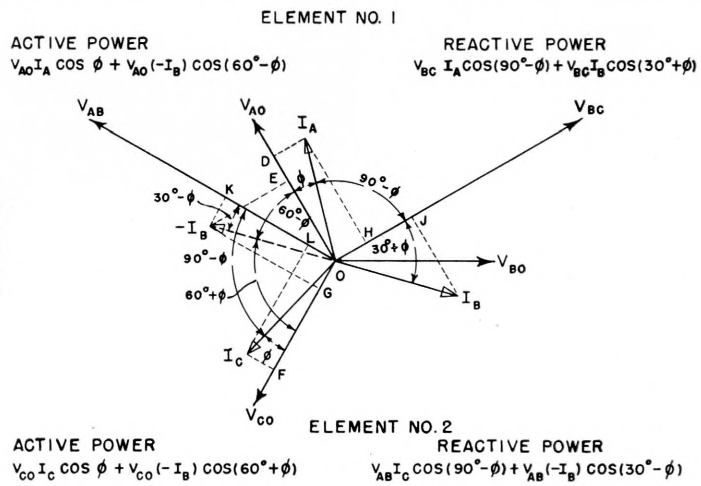


Figure 20—Angular relation between currents and potentials in a three-phase four-wire system when currents lag potentials.

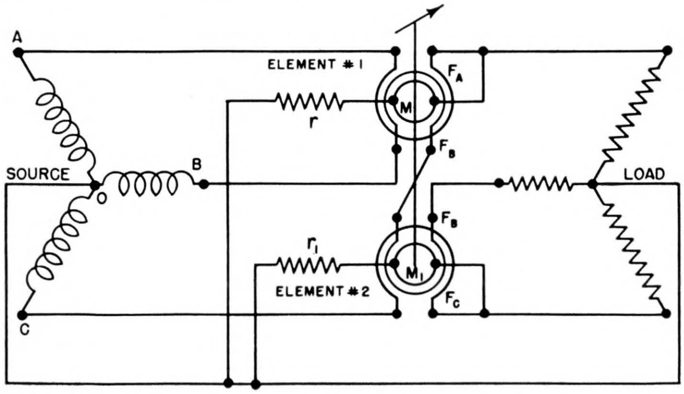


Figure 19—Schematic connections for a two and one-half element wattmeter to a three-phase, four-wire system.

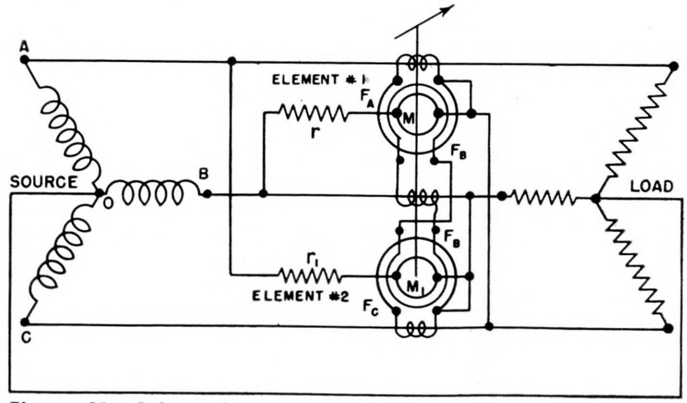


Figure 21—Schematic connections for a two and one-half element varmeter to a three-phase four-wire system using current transformers.

TABLE II
THREE-PHASE FOUR-WIRE CIRCUITS
2½ ELEMENT INSTRUMENT, ADJUSTED FOR ACTIVE POWER
POTENTIALS AND CURRENTS BALANCED

Deg.	Cos Ø or Power Factor	Lagging Ø Element #1	Lagging Ø Element #2	Lagging Ø Total	Leading Ø Element #1	Leading Ø Element #2	Leading Ø Total
Connected to Measure Watts (See Figure 19)							
0	1.00	(+) .50	(+) .50	(+) 1.00	(+) .50	(+) .50	(+) 1.00
30	.87	(+) .58	(+) .29	(+) .87	(+) .29	(+) .58	(+) .87
60	.50	(+) .50	0	(+) .50	0	(+) .50	(+) .50
90	0	(+) .29	(−) .29	0	(−) .29	(+) .29	0
Connected to Measure Vars (See Figure 21)							
Reading Watt Scale as Vars. Divide by 3 for True Vars							
0	1.00	(−) .50	(+) .50	0	(−) .50	(+) .50	0
30	.87	0	(+) .87	(+) .87	(−) .87	0	(−) .87
60	.50	(+) .50	(+) 1.00	(+) 1.50	(−) 1.00	(−) .50	(−) 1.50
90	0	(+) .87	(+) .87	(+) 1.74	(−) .87	(−) .87	(−) 1.74

Referring to Figure 20, when measuring the reactive power, element #1 will indicate in terms of $V_{BC}I_A \cos(90 - \phi) + V_{BC} I_B \cos(30 + \phi)$ and element #2 in terms of $V_{AB}I_C \cos(90 - \phi) + V_{AB}(-I_B) \cos(30 - \phi)$ when the currents lag their respective potentials by the angle ϕ.

With the 2½ element electrodynamometer connected to measure the active or reactive power, the indication of either element or both together should be equal to the volt-amperes taken by the load, $VI\sqrt{3}$ where V is the line volts and I the line current, times the factor found in Table II. The indication will be up-scale (+) or down-scale (—) as shown.

As previously described for three-phase, three-wire systems, a convenient method is to use an auto-transformer to shift the phase and correct the potential value thus allowing the instrument adjusted for active power, to be used for either active or reactive power.

The potential connections for active power as shown in Figure 19 and represented vectorially in Figure 20 are *AO* and *CO*. The potential connections for measuring reactive power are *BC* and *AB* as shown in Figure 21. Since *BC* is $\sqrt{3}$ times *AO*, a tap is made on *BC* at *E* (See Figure 22) so that *BE* = *AO*. This tap *BE* should be 57.7% of *BC*. Likewise a tap *D* is taken on branch *AB* so that *BD* = *CO* = *57.7% of AB*. By means of a four-pole double-throw switch it is possible to use one instrument, adjusted for measuring active power, to measure both active or reactive power.

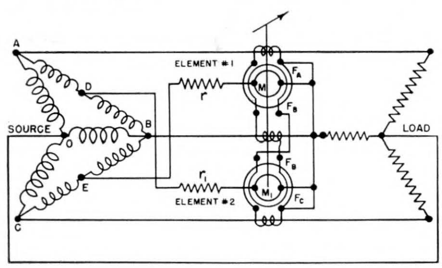


Figure 22—Schematic connections for a two and one-half element varmeter to a three-phase four-wire system using current transformers and a phase shifting reactor.

Reactive power measurements made with the 2½ element instrument are independent of current unbalance, but require the potentials to be balanced.

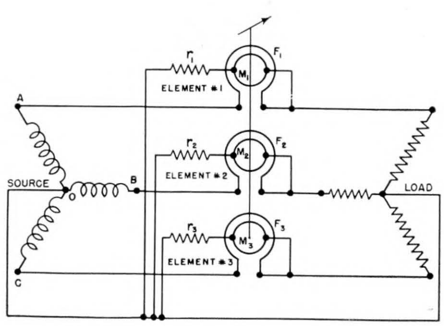


Figure 23—Schematic connections for a three-element wattmeter to a three-phase four-wire system.

A third form of electrodynamometer, composed of three mechanisms so assembled that the potential, or movable coils are mounted to the same staff which carries the pointer and control springs, is available.

When connected as shown in Figure 23 the indication will be the sum of the active power of each phase and is therefore correct for any unbalance. The reactive power may be measured with connections shown in Figure 24. This measurement, however, depends upon the voltage being balanced.

The preceding discussion has been based upon the shifting of the potential connections so as to obtain the quadrature relation. There are variations of this method which include a shift of the current connections. This discussion, however, serves to show the plan most generally used.

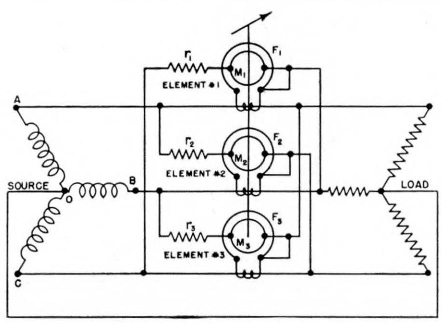


Figure 24—Schematic connections for a three-element varmeter to a three-phase four-wire system using current transformers.

The connection diagrams are shown in schematic forms so as to show more readily the changes desired. Instruments are suitably marked and accompanied by connection diagrams which if followed will take care of the matter of polarity.

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