EEE 322
Experiment 1
3-PHASE POWER MEASUREMENT

I. OBJECTIVES

The primary objectives of the experiment on three-phase ac measurement include becoming familiar with the laboratory equipment as well as reviewing three-phase voltage, current, and complex power relationships studied in previous courses. This experiment also introduced the one-wattmeter and two-wattmeter methods for measuring real power.

II. THEORY AND PREPARATION

First, the basic concept will be described. The single wattmeter (Figure 1) will read (real) power flow from the "left" side to the "right". If $\boldsymbol{V}$ and $\boldsymbol{I}$ are voltage and current phasors at the left side with the reference polarities shown, then the reading of the wattmeter will be

$$P = |\mathbf{V}||\mathbf{I}| \cos\angle \frac{\mathbf{V}}{\mathbf{I}} \quad (1)$$

The reactive power will be

$$Q = \pm|\mathbf{V}||\mathbf{I}| \sin\angle \frac{\mathbf{V}}{\mathbf{I}} \quad (2)$$

where the sign depends on the power factor.

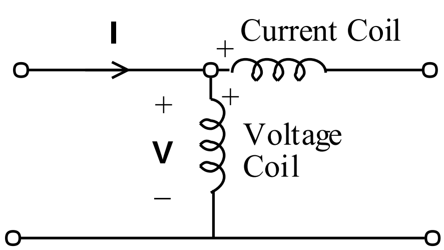

Figure 1 A Wattmeter

Now consider measuring power in a three-phase balanced system. In the three-wattmeter method, three wattmeters will be connected, each from one line to the reference (or neutral). It is easy to see that each wattmeter will read the phase power and the summation would be the total real power. Also, note that no deduction on the sign of reactive power is possible (just as in single wattmeter case).

The two-wattmeter method is an attractive alternative. The connection diagram is given in Figure 2. Any one of the three lines can be taken as the reference; in the figure line b is chosen. Suppose that the readings of the two wattmeters are P_1 and P_2, as marked. The readings P_1 and P_2 depend on the phase sequence and the power factor of the load.

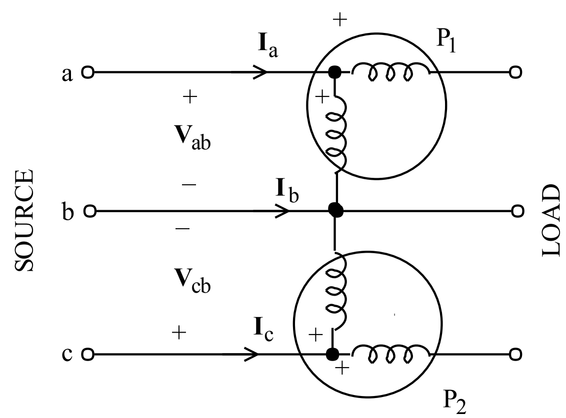

Figure 2 Three-Phase Power Measurement by Two-Wattmeter Method

Students are expected to know the meaning of "abc" and "acb" phase sequences. Figure 3a and 3b are phasor diagrams of phase voltages for abc and acb sequences, respectively. A convenient way to draw line-to-line voltages from phase voltages (or, vice versa) is indicated in Figure 4. N is the centroid (intersection of medians) of the equilateral triangle. Figure 4 is for an abc phase sequence.

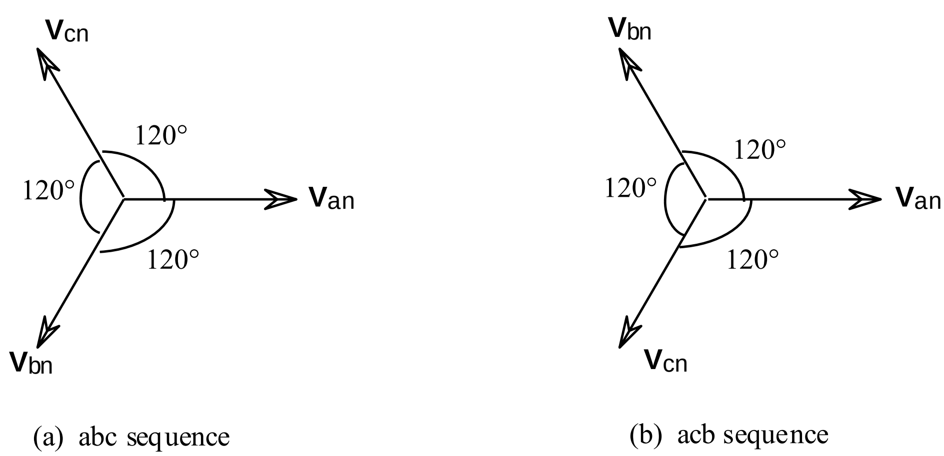

Figure 3 Definition of Phase Sequences

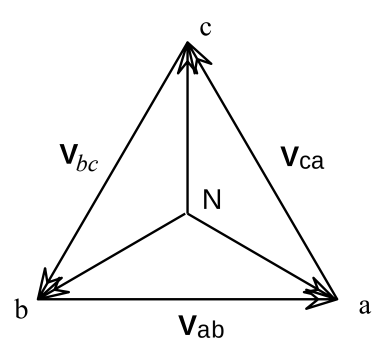

Figure 4 abc sequence

Let us analyze Figure 2 for abc sequence and lagging power factor (p.f.). Suppose that θ is the p.f. angle. The line currents will be displaced from the line-to-neutral voltages by θ. A phasor diagram involving the voltage and current phasors of interest is given in Figure 5.

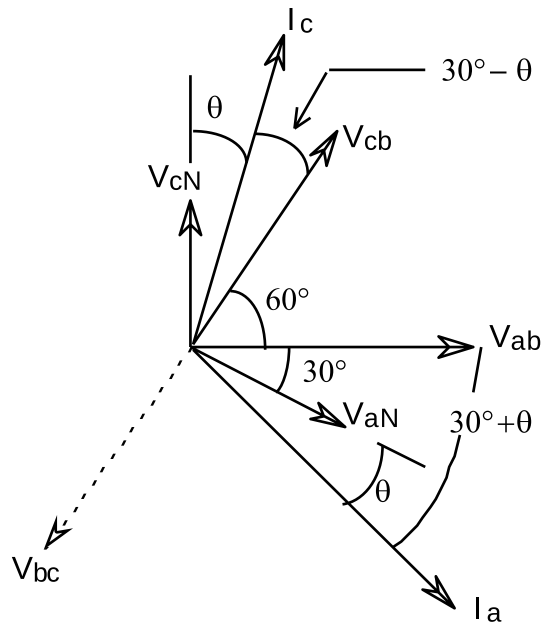

Figure 5 abc sequence and lagging p.f.

Using (1), we write

$$P_1 = |\mathbf{V}_{ab}|\,|\mathbf{V}_a| \cos \angle \frac{\mathbf{V}_{ab}}{\mathbf{V}_a} = V_{LL} I_L \cos(30° + \theta), \quad (3)$$

and

$$P_2 = |\mathbf{V}_{ab}|\,|\mathbf{I}_c| \cos \angle \frac{\mathbf{V}_{cb}}{\mathbf{I}_c} = V_{LL} I_L \cos(30° - \theta). \quad (4)$$

Note that

$$P_1 + P_2 = V_{LL} I_L [\cos(30° + \theta) + \cos(30° - \theta)] = \sqrt{3}\; V_{LL} I_L \cos\theta = P \quad (5)$$

Also,

$$\sqrt{3}\;(P_2 - P_1) = \sqrt{3}\; V_{LL} I_L [\cos(30° - \theta) - \cos(30° + \theta)] = \sqrt{3}\; V_{LL} I_L \sin\theta = Q \quad (6)$$

In the above analysis, the following trigonometric identity was utilized:

$$\cos(A \pm B) = \cos A \;\cos B \mp \sin A \;\sin B \quad (7)$$

For the balanced three-phase system, P and Q are the total 3-ϕ real and reactive power supplied from the source to the load. Both P and Q will be positive (since we are considering lagging power factor).

Results for other three cases are compiled below.

abc sequence, leading power factor

$$P_1 = V_{LL} \; I_L \cos(30° - \theta) \tag{8}$$

$$P_2 = V_{LL} \; I_L \cos(30° + \theta) \tag{9}$$

$$P_1 + P_2 = \sqrt{3} \; V_{LL} \; I_L \cos\theta = P \tag{10}$$

$$\sqrt{3}\,(P_2 - P_1) = -\sqrt{3} \; V_{LL} \; I_L \sin\theta = Q \tag{11}$$

acb sequence, lagging power factor

$$P_1 = V_{LL} \; I_L \cos(30° - \theta) \tag{12}$$

$$P_2 = V_{LL} \; I_L \cos(30° + \theta) \tag{13}$$

$$P_1 + P_2 = \sqrt{3} \; V_{LL} \; I_L \cos\theta = P \tag{14}$$

$$\sqrt{3}\,(P_1 - P_2) = \sqrt{3} \; V_{LL} \; I_L \sin\theta = Q \tag{15}$$

acb sequence, leading power factor

$$P_1 = V_{LL} \; I_L \cos(30° + \theta) \tag{16}$$

$$P_2 = V_{LL} \; I_L \cos(30° - \theta) \tag{17}$$

$$P_1 + P_2 = \sqrt{3} \; V_{LL} \; I_L \cos\theta = P \tag{18}$$

$$\sqrt{3}\,(P_1 - P_2) = -\sqrt{3} \; V_{LL} \; I_L \sin\theta = Q \tag{19}$$

In all cases, θ is considered as the magnitude of the power factor angle. You are urged to draw phasor diagrams (like Fig. 5) for the various cases and verify the expressions for P_1 and P_2. To summarize, note that for all four cases

$$P_1 + P_2 = P \tag{20}$$

and for the abc sequence

$$\sqrt{3}\,(P_2 - P_1) = Q \tag{21}$$

while for the acb sequence

$$\sqrt{3}\left(P_1 - P_2\right) = Q \tag{22}$$

P and Q are, respectively, total real and reactive power supplied from source to load. For leading power factor cases, Q is negative and a reactive power of $\sqrt{3}V_{LL}I_L \sin\theta$ is transferred from the load to the source.

Some more comments follow for the two-wattmeter method.

(1) Power factor is the characteristic of the load, while phase sequence that of the source. Thus, changing phase sequence does not change the power factor.

(2) For any given load, if the phase sequence is reversed, the wattmeter readings are interchanged.

(3) At unity power factor, $P_1 = P_2 = P/2$.

(4) For a power factor of 0.5, one of the two wattmeters will read zero.

(5) The phase angle, θ, and the power factor, cos θ, and be determined from the wattmeter readings alone, if the system is balanced.

$$|\theta| = \tan^{-1}\left(\frac{|Qtotal|}{|Ptotal|}\right)$$

III. LABORATORY WORK

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A. 1-Q Power Measurement

A schematic diagram is given in Figure 1. Make the connections with the aid of the circuit diagram first and then verify with the wiring diagram. The assistant must, however, check the connections.

After getting the "go-ahead" signal from the assistant, apply 100 V to the circuit. By varying the value of rheostat allow a 0.6 A flow through the circuit.

- Measure the load power, voltage and current. Calculate the load power factor.
- By using CRO, measure the phase angle between voltage and current.

De-energize the circuit by pushing STOP on the main panel and turning OFF the power supply. (Remember that no changes in the circuit should be made when it is live.)

B. 3-Q Power Measurement by Two-Wattmeter Method

A schematic diagram is given in Figure 2. Make the connections with the aid of the circuit diagram first and then verify with the wiring diagram. The assistant must, however, check the connections.

After getting the "go-ahead" signal from the assistant, apply 380 V (line to line) to the circuit. Measure line-to-line voltage, line current and the wattmeter's readings.

De-energize the circuit by pushing STOP on the main panel and turning OFF the power supply. (Remember that no changes in the circuit should be made when it is live.). Reverse the phase sequence by interchanging any two lines at the 3-ϕ terminals. Energize the circuit and get data again.

Note: *If the time permits, your assistants may provide another load. Both Part A and Part B will then be repeated for the new load. (This second load should be of a different type in terms of being inductive or capacitive).*

IV. CONCLUSIONS

1. Using the data recorded for the laboratory works, obtain real power, P, complex power magnitude S, and whatever information possible on reactive power, Q, p.f., and the p.f. angle, θ for each part.

2. Discuss the effects of p.f. and the phase sequence on wattmeter readings in the Two-Wattmeter Method.

3. Based on your calculations, identify the load(s). Construct the load(s) as equivalent to a star (Figure 10)). In each case, identify R and the reactance X as an inductance or capacitance.

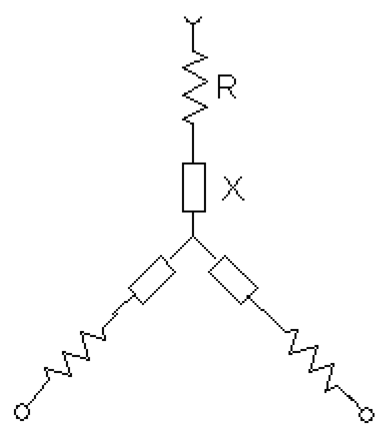
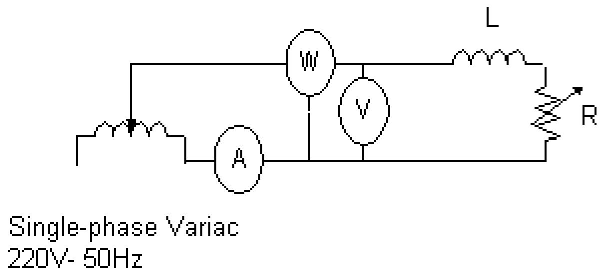


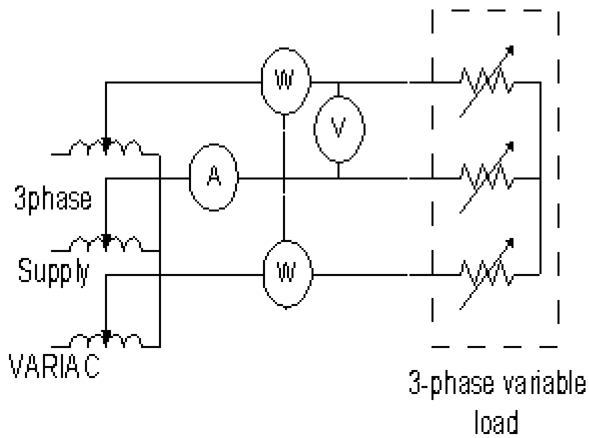
Figure 10. Representations of the 3-Phase Balanced Load



Equipment:

1 single phase variac
1 ammeter, 0-1.2A
1 voltmeter, 0-260V
1 wattmeter 0-5A, 0-240V
1 rheostat 1320 Ω, 0.6 A

Figure 1- Measurement of power and power-factor in a single-phase circuit



Equipment:

1 three-phase variac
1 ammeter, 0-12A
1 voltmeter, 0-260V
1 wattmeter 0-10A, 0-240V
1 three-phase resistive load

Figure 2- Basic connections for two-wattmeter method of power and power-factor measurement of in a three-phase system