

Module 5

Three-phase AC Circuits

Lesson 20

Measurement of Power in a Three-phase Circuit

In the previous lesson, the phase and line currents for balanced delta-connected load fed from a three-phase supply, along with the expression for total power, are presented. In this lesson, the measurement of total power in a three-phase circuit, both balanced and unbalanced, is discussed. The connection diagram for two-wattmeter method, along with the relevant phasor diagram for balanced load, is described.

Keywords: power measurement, two-wattmeter method, balanced and unbalanced loads, star- and delta-connections.

After going through this lesson, the students will be able to answer the following questions:

1. How to connect the two-wattmeter to measure the total power in a three-phase circuit – both balanced and unbalanced?
2. Also how to find the power factor for the case of the above balanced load, from the reading of the two-wattmeter, for the two types of connections – star and delta?

Two-wattmeter Method of Power Measurement in a Three-phase Circuit

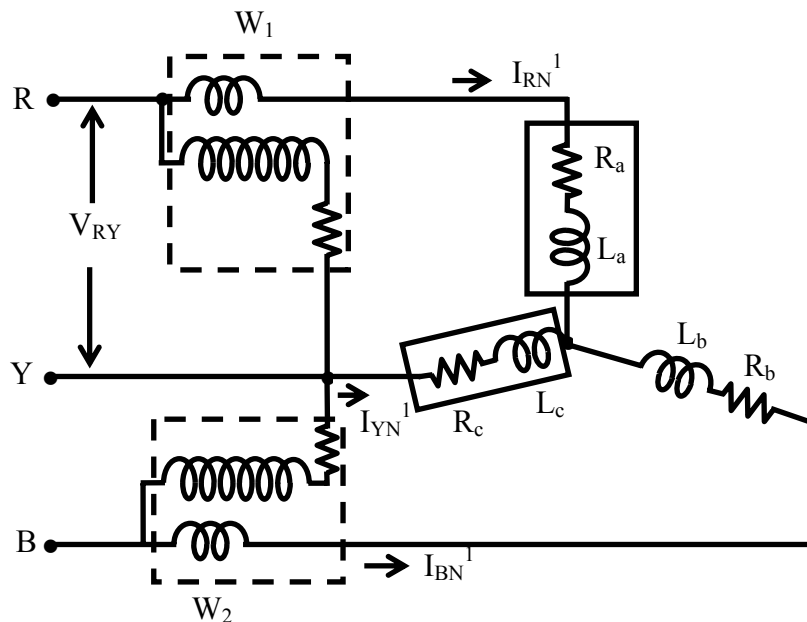


Fig. 20.1 Connection diagram for two-wattmeter method of power measurement in a three-phase balanced system with star-connected load

The connection diagram for the measurement of power in a three-phase circuit using two wattmeters, is given in Fig. 20.1. This is irrespective of the circuit connection – star or delta. The circuit may be taken as unbalanced one, balanced type being only a special case. Please note the connection of the two wattmeters. The current coils of the wattmeters, 1 & 2, are in series with the two phases, R & B, with the pressure or voltage

coils being connected across $R-Y$ and $B-Y$ respectively. Y is the third phase, in which no current coil is connected.

If star-connected circuit is taken as an example, the total instantaneous power consumed in the circuit is,

$$W = i_{RN'} \cdot v_{RN'} + i_{YN'} \cdot v_{YN'} + i_{BN'} \cdot v_{BN'}$$

Each of the terms in the above expression is the instantaneous power consumed for the phases. From the connection diagram, the current in, and the voltage across the respective (current, and pressure or voltage) coils in the wattmeter, W_1 are $i_{RN'}$ and $v_{RY} = v_{RN'} - v_{YN'}$. So, the instantaneous power measured by the wattmeter, W_1 is,

$$W_1 = i_{RN'} \cdot v_{RY} = i_{RN'} \cdot (v_{RN'} - v_{YN'})$$

Similarly, the instantaneous power measured by the wattmeter, W_2 is,

$$W_2 = i_{BN'} \cdot v_{BY} = i_{BN'} \cdot (v_{BN'} - v_{YN'})$$

The sum of the two readings as given above is,

$$W_1 + W_2 = i_{RN'} \cdot (v_{RN'} - v_{YN'}) + i_{BN'} \cdot (v_{BN'} - v_{YN'}) = i_{RN'} \cdot v_{RN'} + i_{BN'} \cdot v_{BN'} - v_{YN'} \cdot (i_{RN'} + i_{BN'})$$

Since, $i_{RN'} + i_{YN'} + i_{BN'} = 0$ or, $i_{YN'} = -(i_{RN'} + i_{BN'})$

Substituting the above expression for $i_{YN'}$ in the earlier one,

$$W_1 + W_2 = i_{RN'} \cdot v_{RN'} + i_{BN'} \cdot v_{BN'} + i_{YN'} \cdot v_{YN'}$$

If this expression is compared with the earlier expression for the total instantaneous power consumed in the circuit, they are found to be the same. So, it can be concluded that the sum of the two wattmeter readings is the total power consumed in the three-phase circuit, assumed here as a star-connected one. This may also be easily proved for delta-connected circuit. As no other condition is imposed, the circuit can be taken as an unbalanced one, the balanced type being only a special case, as stated earlier.

Phasor diagram for a three-phase balanced star-connected circuit

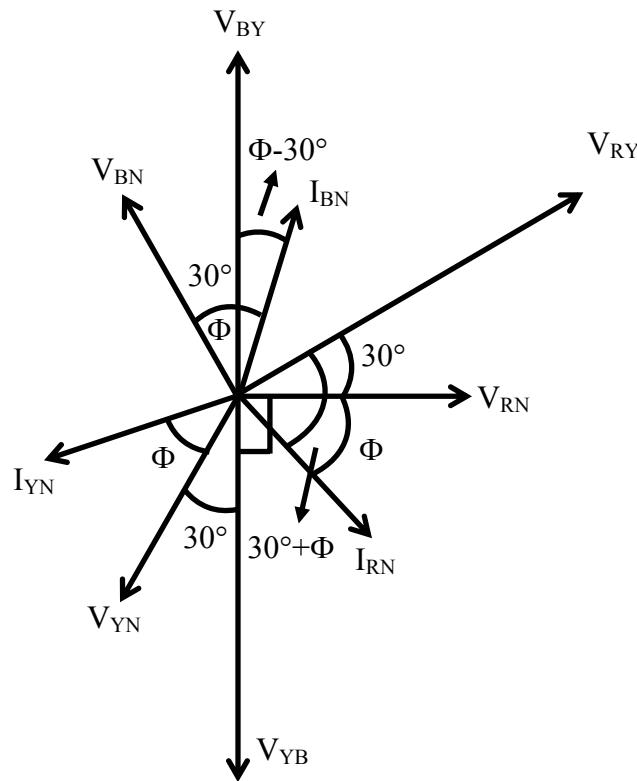


Fig. 20.2 Phasor diagram for two-wattmeter method of power measurement in a three-phase system with balanced star-connected load

The phasor diagram using the two-wattmeter method, for a three-phase balanced star-connected circuit is shown in Fig. 20.2. Please refer to the phasor diagrams shown in the figures 18.4 & 18.6b. As given in lesson No. 18, the phase currents lags the respective phase voltages by $\phi = \phi_p$, the angle of the load impedance per phase. The angle, ϕ is taken as positive for inductive load. Also the neutral point on the load (N') is same as the neutral point on the source (N), if it is assumed to be connected in star. The voltage at that point is zero (0).

The reading of the first wattmeter is,

$$W_1 = V_{RY} \cdot I_{RN} \cdot \cos(V_{RY}, I_{RN}) = V_{RY} \cdot I_{RN} \cdot \cos(30^\circ + \phi) = \sqrt{3} \cdot V_p \cdot I_p \cdot \cos(30^\circ + \phi)$$

The reading of the second wattmeter is,

$$W_2 = V_{BY} \cdot I_{BN} \cdot \cos(V_{BY}, I_{BN}) = V_{BY} \cdot I_{BN} \cdot \cos(30^\circ - \phi) = \sqrt{3} \cdot V_p \cdot I_p \cdot \cos(30^\circ - \phi)$$

The line voltage, V_{RY} leads the respective phase voltage, V_{RN} by 30° , and the phase voltage, V_{RN} leads the phase current, I_{RN} by ϕ . So, the phase difference between V_{RY} & I_{RN} is $(30^\circ + \phi)$. Similarly, the phase difference between V_{BY} & I_{BN} in the second case, can be found and also checked from the phasor diagram.

The sum of the two wattmeter readings is,

$$\begin{aligned} W_1 + W_2 &= \sqrt{3} \cdot V_p \cdot I_p \cdot [\cos(30^\circ + \phi) + \cos(30^\circ - \phi)] = \sqrt{3} \cdot V_p \cdot I_p \cdot 2 \cdot \cos 30^\circ \cdot \cos \phi \\ &= 3 \cdot V_p \cdot I_p \cdot \cos \phi = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos \phi \end{aligned}$$

So, $(W_1 + W_2)$ is equal to the total power consumed by the balanced load.

This method is also valid for balanced delta-connected load, and can be easily obtained.

The phasor diagram for this case is shown in the example No. 20.2.

Determination of power factor for the balanced load

The difference of the two wattmeter readings is,

$$\begin{aligned} W_2 - W_1 &= \sqrt{3} \cdot V_p \cdot I_p \cdot [\cos(30^\circ - \phi) - \cos(30^\circ + \phi)] = \sqrt{3} \cdot V_p \cdot I_p \cdot 2 \cdot \sin 30^\circ \cdot \sin \phi \\ &= \sqrt{3} \cdot V_p \cdot I_p \cdot \sin \phi \end{aligned}$$

If the two sides is multiplied by $\sqrt{3}$, we get

$$\sqrt{3} \cdot (W_2 - W_1) = 3 \cdot V_p \cdot I_p \cdot \sin \phi = \sqrt{3} \cdot V_L \cdot I_L \cdot \sin \phi$$

From the two expressions, we get,

$$\frac{W_2 - W_1}{W_2 + W_1} = \frac{1}{\sqrt{3}} \cdot \tan \phi \quad \text{or,} \quad \phi = \tan^{-1} \left[\sqrt{3} \cdot \left(\frac{W_2 - W_1}{W_2 + W_1} \right) \right]$$

The power factor, $\cos \phi$ of the balanced load can be obtained as given here, using two wattmeter readings.

$$\cos \phi = \frac{1}{\sqrt{1 + \tan^2 \phi}} = \frac{1}{\sqrt{1 + 3 \cdot \left(\frac{W_2 - W_1}{W_2 + W_1} \right)^2}} = \frac{1}{\sqrt{1 + 3 \cdot \left(\frac{1 - y}{1 + y} \right)^2}}$$

$$\text{where, } y = \frac{W_1}{W_2}$$

The two relations, $\cos \phi$ and $\sin \phi$ can also be found as,

$$\cos \phi = \frac{W_1 + W_2}{\sqrt{3} \cdot V_L \cdot I_L} = \frac{W_1 + W_2}{3 \cdot V_p \cdot I_p} \quad \text{and} \quad \sin \phi = \frac{W_2 - W_1}{V_L \cdot I_L} = \frac{W_2 - W_1}{\sqrt{3} \cdot V_p \cdot I_p}$$

Comments on Two Wattmeter Readings

When the balanced load is only resistive ($\phi = 0^\circ$), i.e. power factor ($\cos \phi = 1.0$), the readings of the two wattmeters ($W_1 = W_2 \propto \cos 30^\circ = 0.866(+ve)$), are equal and positive.

Before taking the case of purely reactive (inductive/capacitive) load, let us take first lagging power factor as ($\cos \phi = 0.5$), i.e. $\phi = +60^\circ$. Under this condition,

$$W_1 = 0.0, \text{ as } W_1 \propto \cos(30^\circ + 60^\circ) = \cos 90^\circ = 0.0, \text{ and}$$

$$W_2 \propto \cos(30^\circ - 60^\circ) = \cos 30^\circ = 0.866(+ve) \text{ is positive.}$$

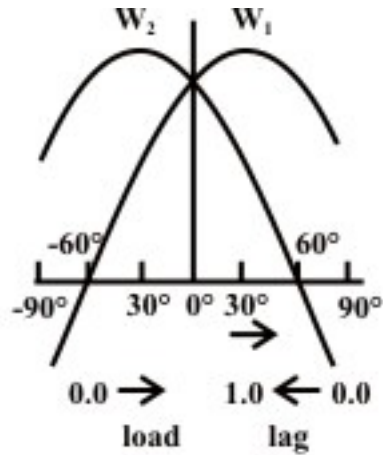


Fig. 20.3 Variation of the readings of two wattmeters (W_1 & W_2) with power factor for a balanced load for the circuit of Fig. 20.1

It may be noted that the magnitudes of the phase or line voltage and also phase current are assumed to be constant, which means that the magnitude of the load impedance (inductive) is constant, but the angle, ϕ varies as stated.

As the lagging power factor decreases from 1.0 to 0.5, with ϕ increasing from 0° to $+60^\circ$, the reading of the first wattmeter, W_1 decreases from a certain positive value to zero (0). But the reading of the second wattmeter, W_2 increases from a certain positive value to positive maximum, as the lagging power factor is decreased from 1.0 to 0.866 ($= \cos 30^\circ$), with ϕ increasing from 0° to $+30^\circ$. As the lagging power factor decreases from 0.866 to 0.5, with ϕ increasing from $+30^\circ$ to $+60^\circ$, the reading of the second wattmeter, W_2 decreases from positive maximum to a certain positive value. It may be noted that, in all these cases, $W_2 > W_1$, with both the readings being positive.

If the lagging power factor is 0.0 ($\phi = +90^\circ$), the circuit being purely inductive, the readings of the two wattmeters ($W_1 = -W_2 \propto \cos(30^\circ + 90^\circ) = \cos 120^\circ = -0.5$) are equal and opposite, i.e., W_1 is negative and W_2 is positive. The total power consumed is zero, being the sum of the two wattmeter readings, as the circuit is purely inductive. This means that, as the lagging power decreases from 0.5 to 0.0, with ϕ increasing from $+60^\circ$ to $+90^\circ$, the reading of the first wattmeter, W_1 decreases from zero (0) to a certain negative value, while the reading of the second wattmeter, W_2 decreases from a certain positive value to lower positive one. It may be noted that $|W_2| > |W_1|$, which means that the total power consumed, i.e., ($W_1 + W_2$) is positive, with only W_1 being negative. The variation of two wattmeter readings as stated earlier, with change in power factor (or phase angle) is now summarized in Table 20.1. The power factor [pf] ($= \cos \phi$) is taken as lagging, the phase current lagging the phase voltage by the angle, ϕ (taken as positive (+ve)), as shown for balanced star-connected load in Fig. 20.2. The circuit is shown in Fig. 20.1. All these are also valid for balanced delta-connected load.

Sl. No.	Power factor [pf] (Phase angle)	Wattmeter readings (W)		Remarks
		W_1	W_2	
1.	pf = unity [1.0] ($\phi = 0^\circ$)	+ve	+ve	$W_1 = W_2$
2.	$0.5 < \text{pf} < 1.0$ ($60^\circ > \phi > 0^\circ$)	+ve	+ve	$W_1 > W_2$
3.	pf = 0.5 ($\phi = 60^\circ$)	+ve	zero (0.0)	Total power = W_1
4.	$0.0 < \text{pf} < 0.5$ ($90^\circ > \phi > 60^\circ$)	+ve	-ve	$ W_1 > W_2 $ (Total power = +ve)
5.	pf = zero [0.0] ($\phi = 90^\circ$)	+ve	-ve	$ W_1 = W_2 $ (Total power = zero (0.0))

Table 20.1 Variation of two wattmeter readings with change in power factor of the load current

It may be noted that, if the power factor is leading ($\phi = \text{negative} (-ve)$), the circuit being capacitive, the readings of the two wattmeters change with the readings interchanging, i.e., W_1 taking the value of W_2 , and vice versa. All the points as stated earlier, remain valid, with the comments as given earlier. The first one (#1) in Table 20.1 is a special case, neither lagging, nor leading, with pf = 1.0. But in second one (#2), both readings remain +ve, with $W_1 < W_2$. Same is the case in fourth one (#4), where W_1 is -ve and W_2 is +ve, with $|W_1| < |W_2|$, total power being positive (+ve). For third case (#3), $W_1 = 0.0$ and W_2 is +ve, with total power = W_2 . For last (fifth) case (#5), W_1 is -ve and W_2 is +ve, with $|W_1| = |W_2|$, total power being zero (0.0).

Power measurement using one wattmeter only for a balanced load

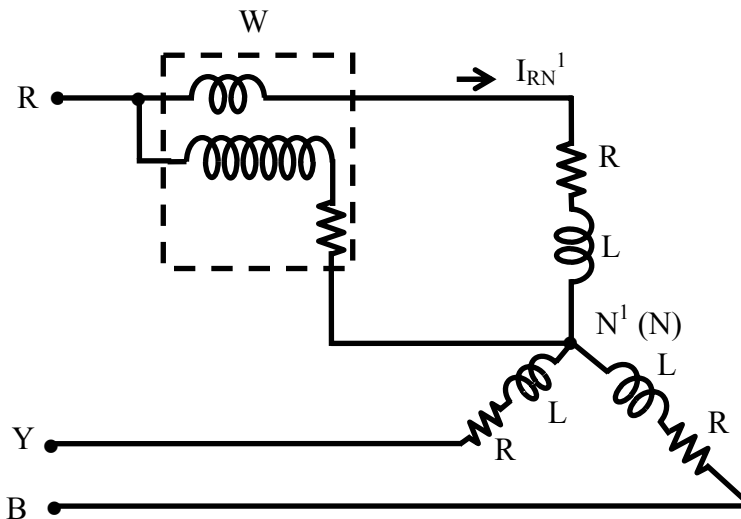


Fig. 20.4 Connection diagram for power measurement using only one wattmeter in a three-phase system with balanced star-connected load

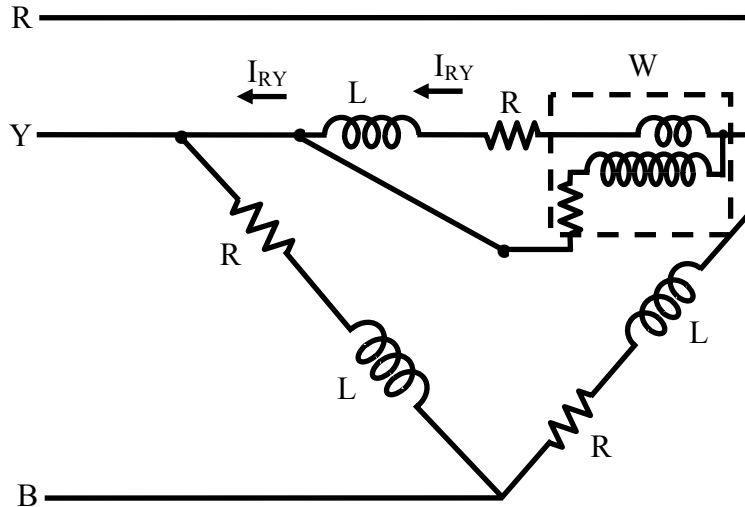


Fig. 20.5 Connection diagram for power measurement using only one wattmeter in a three-phase system with balanced delta-connected load

The circuit diagram for measuring power for a balanced three-phase load is shown in Fig. 20.3. The only assumption made is that, either the neutral point on the load or source side is available. The wattmeter measures the power consumed for one phase only, and the reading is $W = V_p \cdot I_p \cdot \cos \phi$. The total power is three times the above reading, as the circuit is balanced. So, the load must be star-connected and of course balanced one, with the load neutral point being available. The load may also be delta-connected balanced one, if the neutral pinpoint on the source side is available. Otherwise for measuring total power for delta-connected balanced load using one wattmeter only, the connection diagram is given in Fig. 20.4. The wattmeter as stated earlier, measures power for one phase only, with the total power consumed may be obtained by multiplying it by three.

Example 20.1

Calculate the readings of the two wattmeters (W_1 & W_2) connected to measure the total power for a balanced star-connected load shown in Fig. 20.6a, fed from a three-phase, 400 V balanced supply with phase sequence as R-Y-B. The load impedance per phase is $(20 + j15) \Omega$. Also find the line and phase currents, power factor, total power, total reactive VA and total VA.

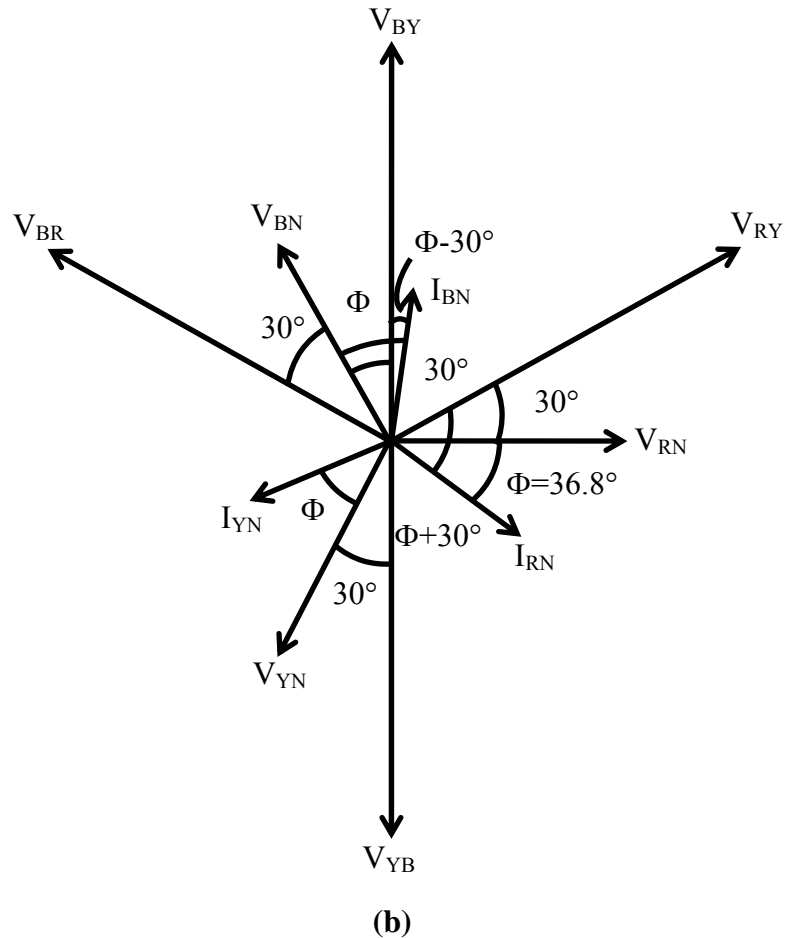
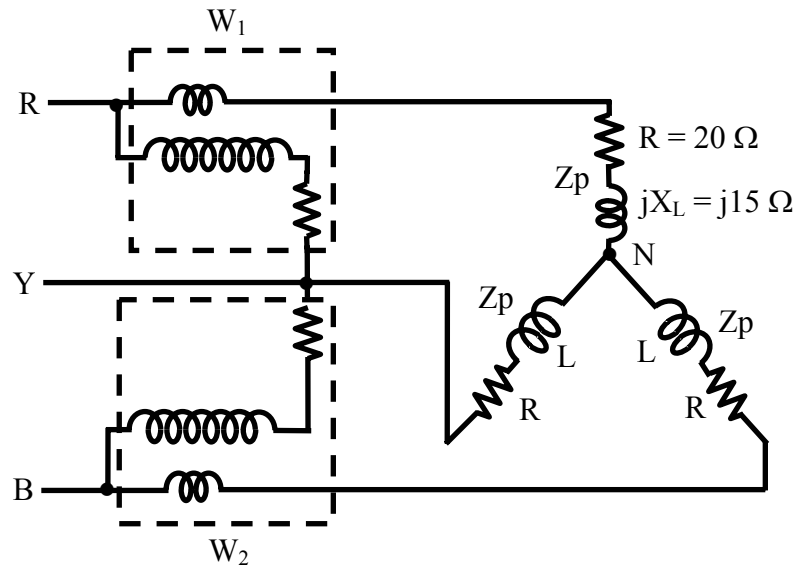


Fig. 20.6 (a) Circuit diagram for a three-phase system with balanced star-connected load (Example 20.1)
(b) Phasor diagram

Solution

$$|V_L| = 400 \text{ V} \quad Z_{RN} = Z_p = 20 + j15 = 25 \angle +36.87^\circ \Omega$$

As the star-connected load is balanced, the magnitude of the phase voltage is,

$$|V_p| = |V_L|/\sqrt{3} = 400/\sqrt{3} = 231 \text{ V}$$

Taking the phase voltage, V_{RN} as reference, the phase voltages are,

$$V_{RN} = 231 \angle 0^\circ; \quad V_{YN} = 231 \angle -120^\circ; \quad V_{BN} = 231 \angle +120^\circ$$

The phasor diagram is shown in Fig. 20.6b. It has been shown that the line voltage, V_{RY} leads the corresponding phase voltage, V_{RN} by 30° . So, the line voltages are,

$$V_{RY} = 400 \angle +30^\circ; \quad V_{YB} = 400 \angle -90^\circ; \quad V_{BR} = 400 \angle +150^\circ$$

For a star-connected load, the phase and the line currents are same.

The current in R-phase is,

$$I_{RN} = I_R = V_{RN} / Z_p = (231.0 \angle 0^\circ) / (25.0 \angle +36.87^\circ) = 9.24 \angle -36.87^\circ \text{ A} \\ = (7.39 - j5.54) \text{ A}$$

Two other phase and line currents are,

$$I_{YN} = I_Y = 9.24 \angle -156.87^\circ \text{ A}; \quad I_{BN} = I_B = 9.24 \angle +83.13^\circ \text{ A}$$

The power factor of the load is $\cos \phi = \cos 36.87^\circ = 0.8$ lagging, with $\phi = +36.87^\circ$, as the load is inductive.

$$\text{Total VA} = 3 \cdot V_p \cdot I_p = 3 \times 231.0 \times 9.24 = 6.403 \text{ kVA}$$

$$\text{This can be taken as } \sqrt{3} \cdot V_L \cdot I_L = \sqrt{3} \times 400 \times 9.24 = 6.403 \text{ kVA}$$

$$\text{Total power} = 3 \cdot V_p \cdot I_p \cdot \cos \phi = 3 \times 231.0 \times 9.24 \times 0.8 = 5.123 \text{ kW}$$

$$\text{Total reactive VA} = 3 \cdot V_p \cdot I_p \cdot \sin \phi = 3 \times 231.0 \times 9.24 \times \sin 36.87^\circ = 3.842 \text{ kVAR}$$

The readings of the two wattmeters are,

$$W_1 = V_{RY} \cdot I_R \cdot \cos (30^\circ + \phi) = 400 \times 9.24 \times \cos 66.87^\circ = 1.45 \text{ kW}$$

The phase angle between V_{RY} and I_R is 66.87° , obtained using two phasors.

$$W_2 = V_{BY} \cdot I_B \cdot \cos (30^\circ - \phi) = 400 \times 9.24 \times \cos 6.87^\circ = 3.67 \text{ kW}$$

The phase angle between V_{BY} and I_B is 6.87° , obtained using two phasors, where $V_{BY} = 400 \angle +90^\circ$.

The sum of two readings is $(1.45 + 3.67) = 5.12 \text{ kW}$, which is same as the total power computed earlier

Example 20.2

Calculate the readings of the wattmeter (W) connected as shown in Fig. 20.7a. The load is the same, as in Fig. 20.7a (Ex. 20.1), i.e., balanced star-connected one, with impedance of $(20 + j15) \Omega$ per phase, fed from a three-phase, 400 V, balanced supply, with the phase sequence as R-Y-B.

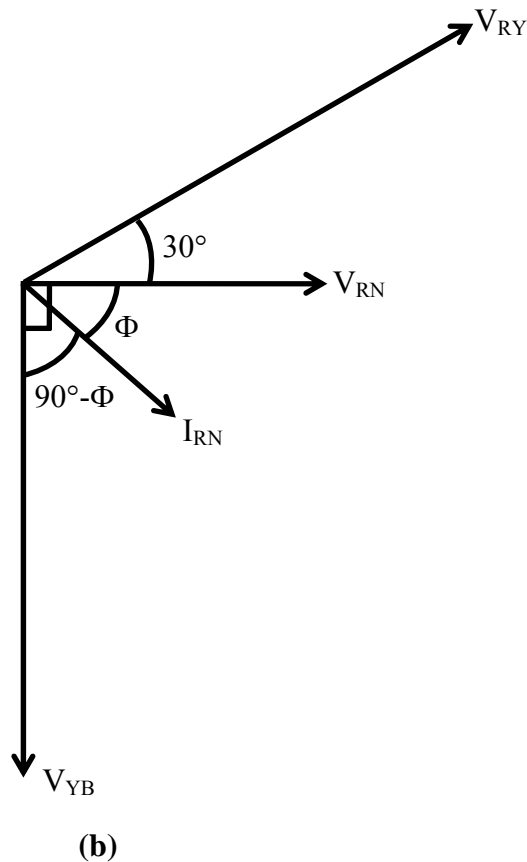
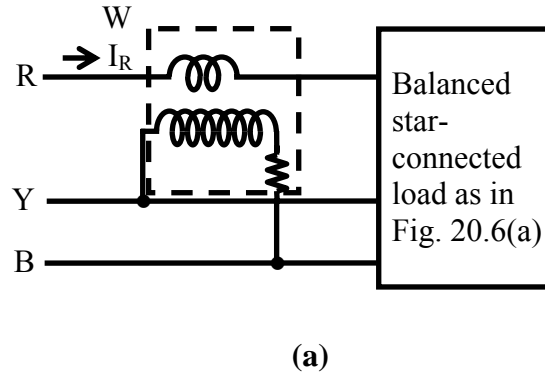


Fig. 20.7 (a) Circuit diagram (Example 20.2)
(b) Phasor diagram

Solution

The steps are not repeated here, but taken from previous example (20.1).

The phasor diagram is shown in Fig. 20.7b.

The phase voltage, V_{RN} is taken as reference as in Ex. 20.1.

The phase current, I_{RN} is $I_{RN} = 9.24 \angle -36.87^\circ \text{ A}$

The phase angle, ϕ of the load impedance is $\phi = +36.87^\circ$

The line voltage, V_{RY} is $V_{RY} = 400 \angle +30^\circ \text{ V}$

The line voltage, V_{YB} is $V_{YB} = 400 \angle -90^\circ \text{ V}$

The reading of the wattmeter (W) is,

$$W = V_{YB} \cdot I_{RN} \cdot \cos(V_{YB}, I_{RN}) = V_L \cdot I_p \cdot \cos(90^\circ + \phi) = -\sqrt{3} \cdot V_p \cdot I_p \cdot \sin \phi$$

$$= -400 \times 9.24 \times \sin 36.87^\circ = -2.218 \text{ kW}$$

The value is negative, as the load is inductive.

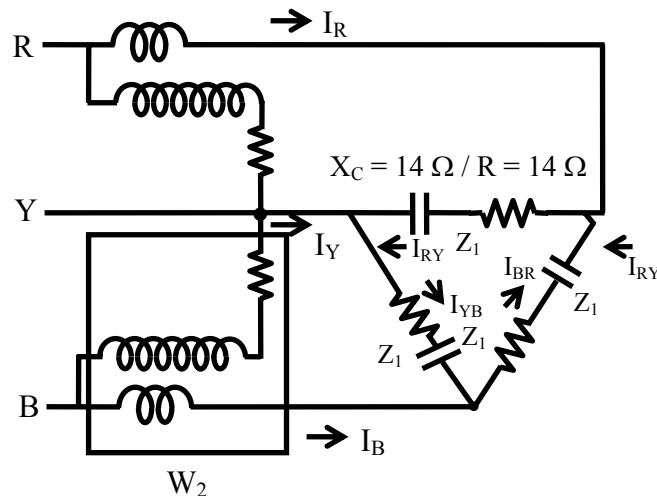
The reading (W) is $1/\sqrt{3} = 0.577$ times the total reactive power as,

$$3 \cdot V_p \cdot I_p \cdot \sin \phi = \sqrt{3} \cdot V_L \cdot I_L \cdot \sin \phi ,$$

or $\sqrt{3}$ times the reactive power per phase.

Example 20.3

Calculate the readings of the two wattmeters (W_1 & W_2) connected to measure the total power for a balanced delta-connected load shown in Fig. 20.8a, fed from a three-phase, 200 V balanced supply with phase sequence as R-Y-B. The load impedance per phase is $(14 - j14) \Omega$. Also find the line and phase currents, power factor, total power, total reactive VA and total VA.



The procedure is only presented, with the steps given in brief.

$$\text{Total VA} = 3 \cdot V_p \cdot I_p = 3 \times 200.0 \times 10.1 = 6.06 \text{ kVA}$$

$$\text{This can be taken as } \sqrt{3} \cdot V_L \cdot I_L = \sqrt{3} \times 200 \times 17.5 = 6.06 \text{ kVA}$$

$$\text{Total power} = 3 \cdot V_p \cdot I_p \cdot \cos \phi = 3 \times 200.0 \times 10.1 \times 0.707 = 4.285 \text{ kW}$$

$$\text{Total reactive VA} = 3 \cdot V_p \cdot I_p \cdot \sin \phi = 3 \times 200.0 \times 10.1 \times \sin 45^\circ = 4.285 \text{ kVAR}$$

The readings of the two wattmeters are,

$$W_1 = V_{RY} \cdot I_R \cdot \cos(30^\circ + \phi) = 200 \times 17.5 \times \cos(-15^\circ) = 3.38 \text{ kW}$$

The phase angle between V_{RY} and I_R is 15° , obtained using two phasors.

$$W_2 = V_{BY} \cdot I_B \cdot \cos(30^\circ - \phi) = 200 \times 17.5 \times \cos 75^\circ = 0.906 \text{ kW}$$

The phase angle between V_{BY} and I_B is 75° , obtained using two phasors, where

$$V_{BY} = 200 \angle +60^\circ.$$

The sum of two readings is $(3.38 + 0.906) = 4.286 \text{ kW}$, which is same as the total power computed earlier

Alternatively, the phase current, I_{RY} can be taken as reference, with the corresponding phase voltage, V_{RY} leading the current by the angle of the load impedance, $\phi = 45^\circ$. So, the phase current and voltage are,

$$I_{RY} = 10.1 \angle 0^\circ \text{ A}; \quad V_{RY} = I_{RY} \angle 0^\circ \cdot Z_p \angle \phi = (10.1 \times 19.8) \angle 45^\circ = 200 \angle 45^\circ \text{ V}$$

Two other phase currents and voltages are,

$$I_{YB} = 10.1 \angle -120^\circ; \quad I_{BR} = 10.1 \angle +120^\circ$$

$$V_{YB} = 200 \angle -75^\circ; \quad V_{BR} = 200 \angle +165^\circ$$

The line current, I_R is,

$$I_R = I_{RY} - I_{BR} = 10.1 \angle 0^\circ - 10.1 \angle +120^\circ = 17.5 \angle +30^\circ \text{ A}$$

Two other line currents are,

$$I_Y = 17.5 \angle -90^\circ; \quad I_B = 17.5 \angle +150^\circ$$

The other steps are not shown here. The readers are requested to study the previous lesson (No. 19) in this module.

The measurement of power using two wattmeters for load (unbalanced or balanced), fed from a balanced three-phase supply, is discussed in this lesson. Also presented are the readings of the two wattmeters for balanced load, along with the determination of the load power factor from the two readings, and some comments on the way, the two readings vary with change in power factor of the load, with the magnitude of the load impedance remaining constant. Some examples are also described here. This is the last lesson in this module (No.5). In the next module (No.6) consisting of two lessons (no. 21-22) only, the discussion on magnetic circuits will be taken up.

- 20.1 Calculate the reading of the two wattmeter's (W_1 , and W_2) connected to measure the power for a balanced three-phase load as given in the following. The supply voltage is 200V and the phase.

- i. The connections of the wattmeter, W_1 – current coil is in phase R, and the voltage coil is across R and Y
- ii. The connections of the wattmeter, W_2 – current coil is in phase B, and the voltage coil is across B and Y

Draw the phasor diagram

- a. star- connected balanced load with $(9-j5) \Omega$ per phase
 - b. delta-connected balanced load with $(14+j14) \Omega$ per phase.
- 20.2 The two wattmeter reading for a balanced three-phase load, are 300W and 100W respectively with the watt meter as given in Prob 20.1. Calculate the total power, the line current, the power factor, and also the reactive VA.
- 20.3 A balanced delta-connected load with 50Ω per phase (Fig. 20.9), is fed from a three-phase 200V supply. Find the reading of the wattmeter.

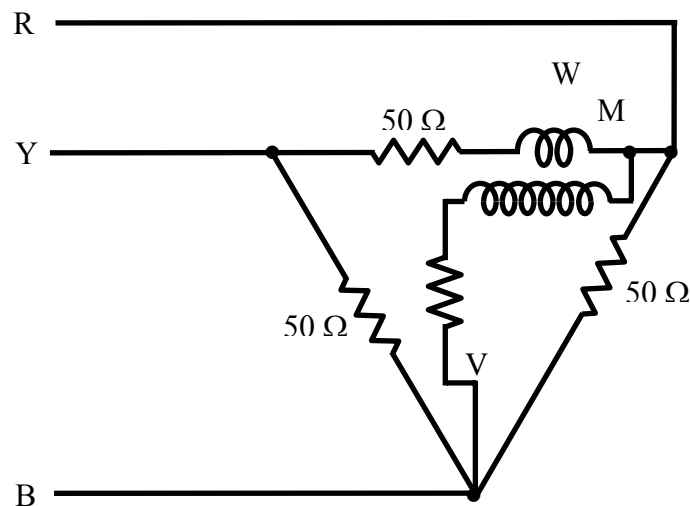


Fig. 20.9

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