Lesson 7: Power and Energy Measurement

ET 332b Ac Motors, Generators and Power Systems

Learning Objectives

After this presentation you will be able to:

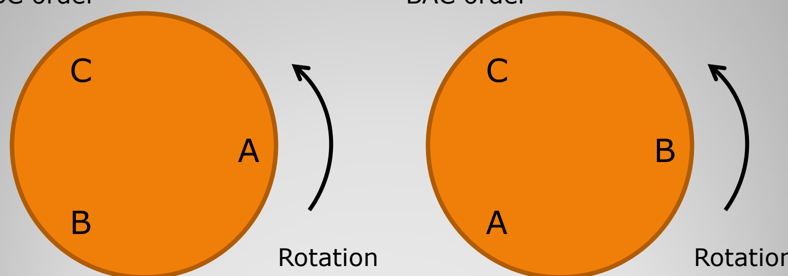
- Determine the phase sequence of a 3-phase voltage source
- Explain the difference between single and 3-phase ac power flow in time
- Connect power meters to read active power and reactive power
- Explain how energy meters operate
- Read and compute energy consumption

Phase Sequence in 3-Phase Systems

Phase Sequence - order of voltages in a 3-phase system. Determine the direction of rotation in motors and the direction of flow in power and energy measurement

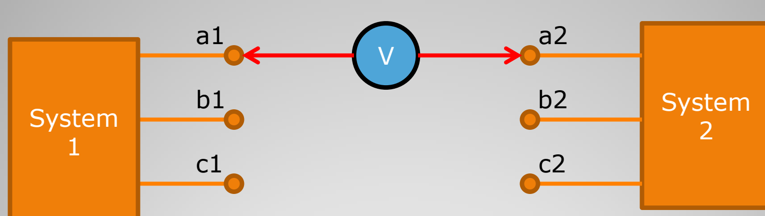
Positive sequence: Phase voltages and currents have ABC order

Negative sequence: Phase voltages and currents have BAC order

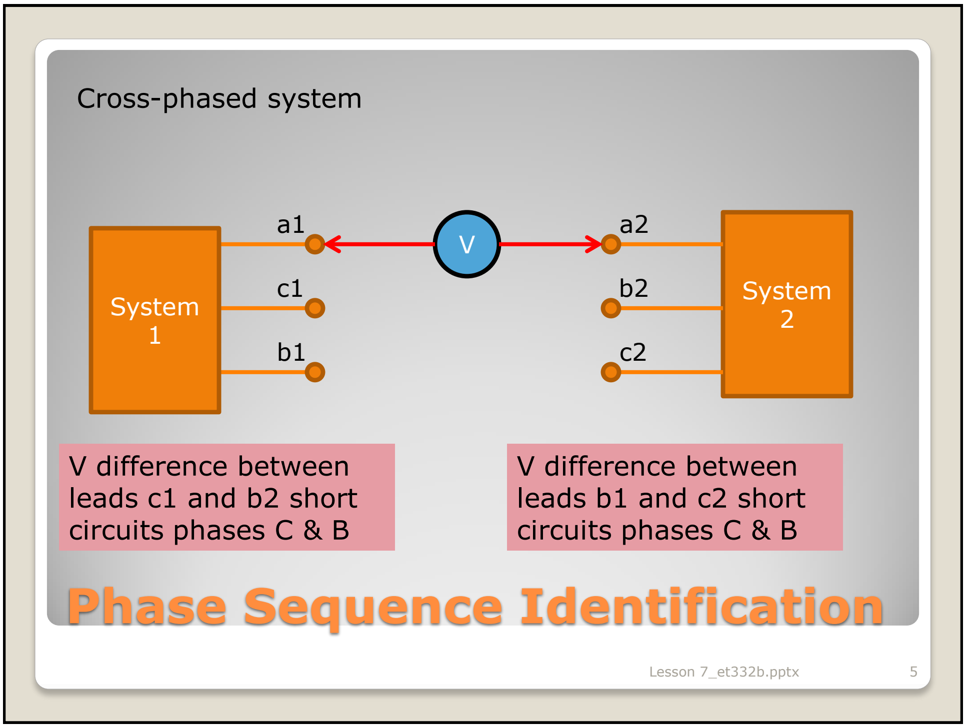


Phase Sequence Identification

Phase sequence of interconnected power systems must match. Identify phase lead of each system using voltmeter



V-meter measures no potential difference if a1 is in phase with a2


Cross-phased system
a1
c1
b1
System 1
V
a2
b2
c2
System 2
V difference between leads c1 and b2 short circuits phases C & B
V difference between leads b1 and c2 short circuits phases C & B
Phase Sequence Identification
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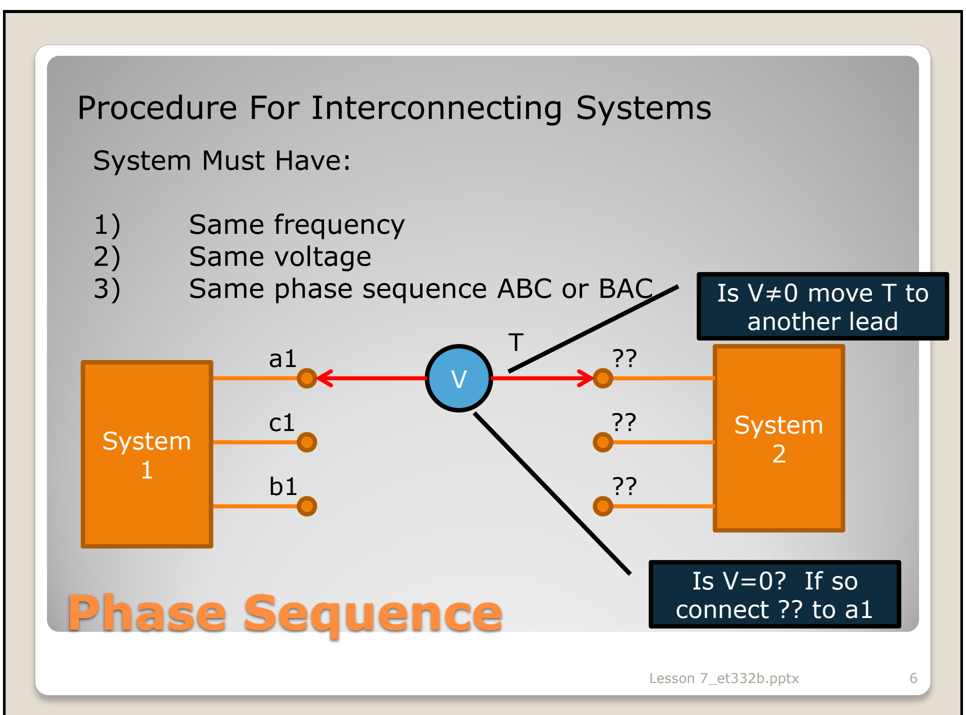
Procedure For Interconnecting Systems
System Must Have:
1) Same frequency
2) Same voltage
3) Same phase sequence ABC or BAC
Is V≠0 move T to another lead
T
a1
c1
b1
System 1
V
??
??
??
System 2
Is V=0? If so connect ?? to a1
Phase Sequence
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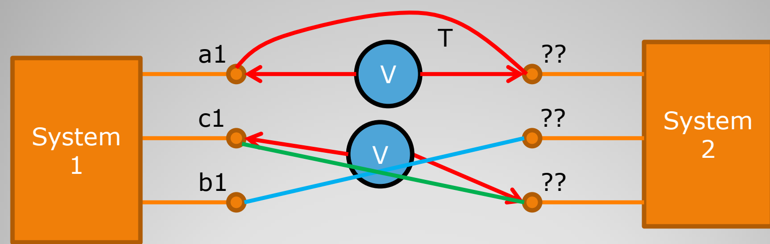
Phase Sequence

Example 7-1: determine the correct connections to tie the two systems together



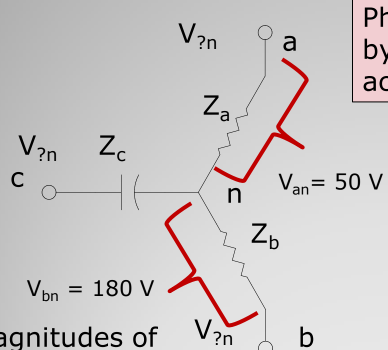
1) a1-??: V=0 connect leads

2) c1-?? V≠0 move T lead

3) c1-??: V=0 connect leads

Phase Sequence Indicator

Simple indicator uses unbalanced Y-connection with no ground



Magnitudes of $|Z_a|=|Z_b|=|Z_c|$

Phase sequence determined by voltage measurements across phase to neutral

Sequence:
V-high (A),
V-low (B),
Capacitor (C)

Example:

Phase Sequence BAC

Balanced 3-phase V's produce balanced I's

$$V_a(t) = V_m \sin(\omega t)$$
$$V_b(t) = V_m \sin(\omega t - 120^\circ)$$
$$V_c(t) = V_m \sin(\omega t + 120^\circ)$$

$$I_a(t) = I_m \sin(\omega t - \theta)$$
$$I_b(t) = I_m \sin(\omega t - 120^\circ - \theta)$$
$$I_c(t) = I_m \sin(\omega t + 120^\circ - \theta)$$

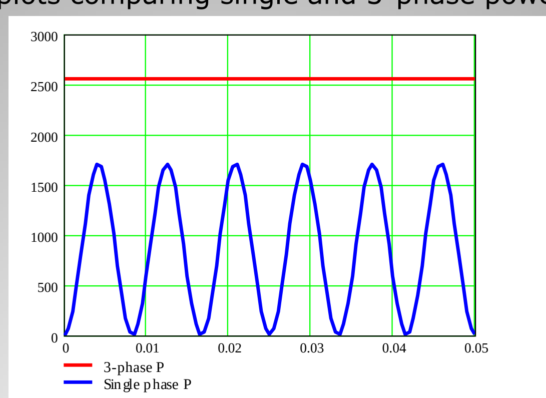
θ=power factor angle

Single phase power $P_{1\phi}(t) = V_a(t) \cdot I_a(t)$

3-phase power $P_{3\phi}(t) = V_a(t) \cdot I_a(t) + V_b(t) \cdot I_b(t) + V_c(t) \cdot I_c(t)$

Time Functions of AC power

Power time plots comparing single and 3-phase power

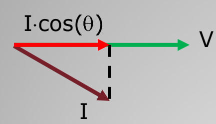


Note: Three phase power does not change in time. Single phase power instantaneously zero.

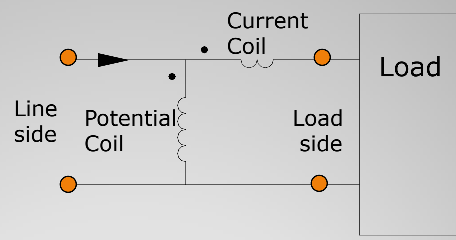
Time Functions of AC power

Active power measurement requires measurement of both I and V

$P = V \cdot I \cdot \cos(\theta)$



Metering connections



Dotted ends of coils indicate instantaneously positive potentials and currents

Meters can be connected to measure positive for load entering or leaving the load. Convention: I entering dot gives positive P. Indicates load absorbs P. I leaving dot- negative P, load delivers P

Single Phase Power Measurements

Blondel's Theorem - Number of meters required to measure total power in balanced three-phase system is given by

number meters = number wires -1

Example 7-2:

3 phase 3-wire delta system
2-meters
3 phase 4-wire wye system
3-meters
3 phase 3 wire wye system
2-meters

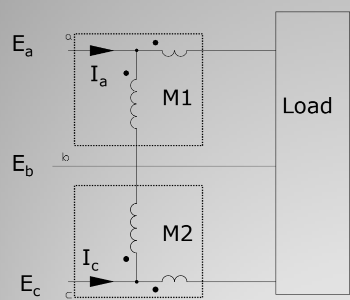
2 elements

3 elements

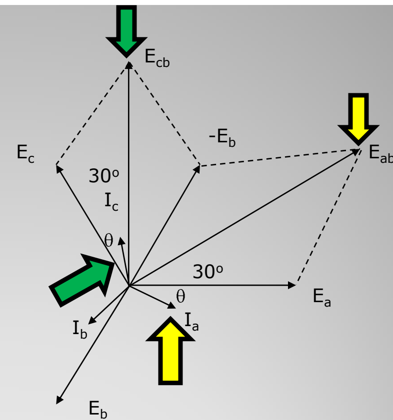
Meters can be integrated into single unit that displays total power. Each integral meter is called an **element**

Three-phase Power Metering

Two-wattmeter method



$P_T = P_{M1} + P_{M2}$



Meter M1 measures E_{ab} and I_a

$$P_{M1} = V_{ab} \cdot I_a \cdot \cos(30^\circ + \theta)$$

Meter M2 measures E_{cb} and I_c

$$P_{M2} = V_{cb} \cdot I_c \cdot \cos(30^\circ - \theta)$$

Three-wire Connections

Derivation

$$P_T = P_{M1} + P_{M2} = E_{ab} I_a \cos(30^\circ + \theta) + E_{cb} I_c \cos(30^\circ - \theta)$$

Since $I_a = I_c = I_L$ and $E_{ab} = E_{cb} = E_{LL}$

$$P_T = P_{M1} + P_{M2} = E_{LL} I_L (\cos(30^\circ + \theta) + \cos(30^\circ - \theta))$$

Simplify using trigonometric identities

$$(\cos(30^\circ + \theta) + \cos(30^\circ - \theta)) = \sqrt{3}\cos(\theta)$$

$$P_T = P_{M1} + P_{M2} = \sqrt{3}\, E_{LL} I_L \cos(\theta)$$

Two meters read total power

2-Wattmeter Power Measurement

Reading of meter M1 changes as load F_p changes

$\theta = 60^o$ then $30^o + \theta = 90^o$ so $\cos(90^o) = 0$ and $P_{M1} = 0$

$F_p = \cos(60^o) = 0.5$

M1 reads negative for $F_p < 0.5$
M1 reads positive for $F_p > 0.5$
M1 reads zero for $F_p = 0.5$

2-Wattmeter Power Measurement

Example 7-3: A balanced 3-phase 3-wire load is measured using the 2-wattmeter method. The line current for the load is 125 A and the system voltage is 575 volts. The load has a power factor of 45% (0.45) lagging. Find the total load power and the readings for each meter.

$$F_p = \cos(\theta) = 0.45$$

$$P_T = \sqrt{3}\, E_{LL} I_L \cos(\theta) = \sqrt{3}\,(575)(125)(0.45) = 56{,}021\ \text{W}$$

Compute the reading on meter 1 and meter 2 using the equations for meter's 1 and 2

2-Wattmeter Example

Example 7-3 Solution (1)

Using the formulas for M1 and M2 we get these values

$$\theta = \cos^{-1}(F_p) = \cos^{-1}(0.45) = 63.2^{\circ}$$

$$P_{M1} = E_{LL} I_L \cos(30+\theta) = (575)(125)\cos(30+63.2)$$

$$P_{M1} = 71875 \cdot \cos(93.2) = -4012 \text{ W}$$

$$P_{M2} = 71875\cos(30-\theta) = 71875\cos(-33.2)$$

$$P_{M2} = 60142 \text{ W}$$

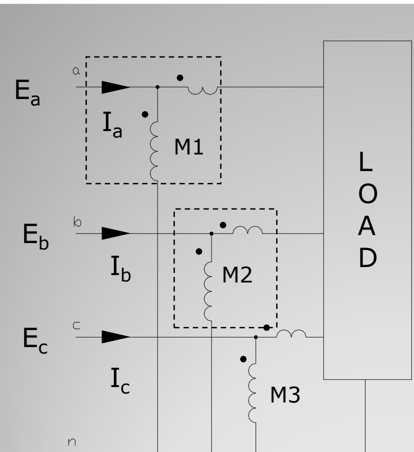
Check total value: P_T = 60142-4012 = 56130 W

Finding F_p from M1 and M2 readings

$$\tan(\theta) = \sqrt{3} \cdot \frac{P_{M2} - P_{M1}}{P_{M2} + P_{M1}}$$

$$F_p = \cos(\theta)$$

Three-Phase, 4-wire Metering Connections



Requires a three element meter or 3 single meters

Each meter measures phase voltages and currents so

$P_T = P_{M1} + P_{M2} + P_{M3}$

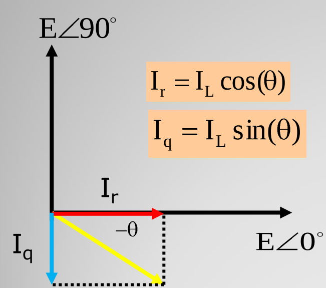
Current entering load gives positive P readings with ABC phase sequence.

Reactive Power Metering

VAR and kVAR Metering

All P and Q meters measure the current components that are in phase with the load voltage.

For single phase measurements



CCW phase rotation

$$I_r = I_L\cos(\theta)$$

$$I_q = I_L\sin(\theta)$$

Active power

$$P_T = EI_L\cos(\theta)$$

Reactive power

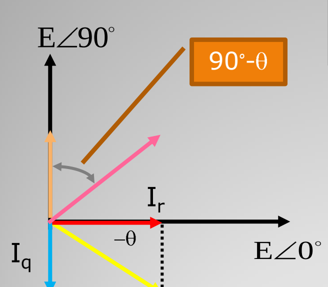
$$Q_T = EI_L\sin(-\theta)$$

$$Q_T = EI_L\cos(90+\theta)$$

$$Q_T = -EI_L\sin(\theta)$$

Reactive Power Metering

Sign convention of reactive power



CCW phase rotation

Lagging current produces a negative VAR reading

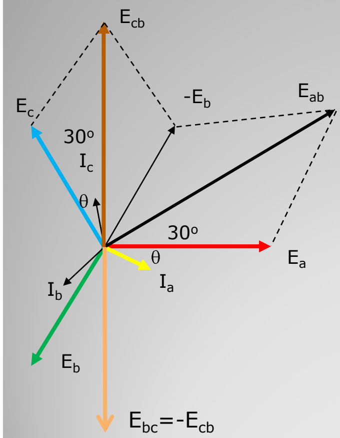
$$Q_T = -EI_L\sin(\theta)$$

For leading current:

$$Q_T = EI_L\cos(90-\theta) = EI_L\sin(\theta)$$

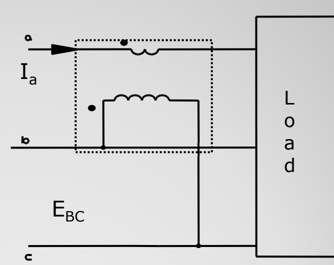
Leading current produces a positive VAR reading with this phase rotation

VAR Measurement By Cross-Phasing Voltage



Meter measures current in phase "a" and the line- to-line voltage E_{bc}. This gives the following relationship

$$Q_T = \pm\sqrt{3}E_{bc}I_a\sin(\theta) = \sqrt{3}E_{LL}I_L\sin(\theta)$$



Reactive Power Measurement

Measuring VARs from the two-watt meter method

$$P_2 - P_1 = E \cdot I \cdot \sin(\theta) = Q$$

To get total VARs, multiply both sides by square root of 3.

$$\sqrt{3}\cdot(P_2 - P_1) = \sqrt{3}\cdot E_{LL}\cdot I_L\cdot\sin(\theta) = Q_T$$

$$Q_T = \sqrt{3}\cdot(P_2 - P_1)$$

P_2 reading of meter between phases b and c

Reactive Power Measurement

Reactive Power Measurement Two-Wattmeter Method

Example 7-4: The two-wattmeter connection shown below measures the power input to a load. The reading of wattmeter M1 is 5000 W and wattmeter M2 is 12,000 W. From these readings find: a.) Total active power absorbed, b.) total reactive power absorbed, c.) F_p of the load.

a) Total active power

$$P_T = P_{m1} + P_{m2}$$

$$P_{m1} = 5000\ \text{W}$$
$$P_{m2} = 12{,}000\ \text{W}$$

$$P_T = 5{,}000 + 12{,}000$$

$$P_T = 17{,}000\ \text{W}$$ Ans

Example 7-4 Solution (1)

b) Reactive power

$$Q_T = \sqrt{3}\,(P_{m2} - P_{m1})$$

$$Q_T = \sqrt{3}\,(12{,}000 - 5{,}000)$$
$$Q_T = \sqrt{3}\,(7000)$$

$$Q_T = 12{,}124\ \text{VAR}$$ Ans

c) Find power factor

$$F_p = \frac{P_T}{S_T} \qquad S_T = \sqrt{P_T^2 + Q_T^2}$$

$$S_T = \sqrt{17{,}000^2 + (12{,}124)^2}$$

$$S_T = 20{,}881\ \text{VA}$$

$$F_p = \frac{17{,}000\ \text{W}}{20{,}881\ \text{VA}}$$

$$F_p = 0.814\ \text{Lag}$$ Ans

High Voltage and High Current Power Measurements

Instrument transformers reduce voltage and current to measurable range.

Potential Transformers (PT)

Reduce voltage from high potential to 110-120 V range Typical ratios 6900/115 = 60/1 PTR

Current Transformer (CT)

Reduce high currents to 1-10A range meters rated 5 A nominal 10 A overload. Typical ratio 600/5 = 120/1 CTR

Scaling factor for high power metering

Power ratio = (CTR)(PTR) for above case
Power ratio = (120)(60) = 7200

Electric Energy Measurement

ENERGY = (instantaneous power) x (time)

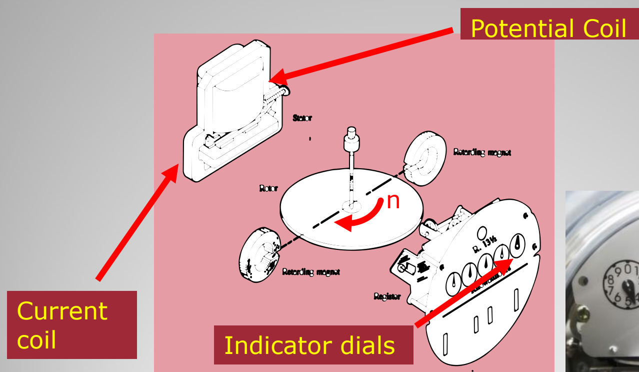
W = p x t where W = energy
p = instantaneous power
t = time

Electromechanical kWh meters sum power over time interval using a rotating disk.

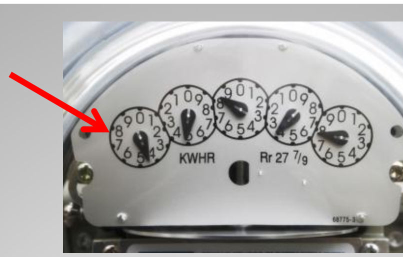
Number of revolutions, n, proportional to energy

so $n = C_p \times P \times t$

C_p = meter energy constant (units kWh/rev) kWh meter measures the electric energy we all consume in our homes and businesses



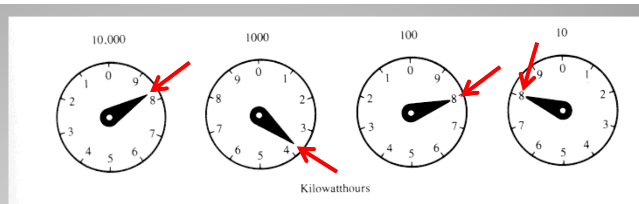
Electromechanical Energy Meter Construction



1) Start from left-most Dial (10,000)
2) Record value just past by pointer
3) Record value of each dial
4) Subtract last reading from present meter reading
5) Difference is the usage in kWh for period

How to Read an Electromechanical Energy Meter

Example 7-5



Compute the usage for the last 30 days if the last meter reading was 7129 and the current meter reading is shown above

Note rotation directionof the meter dials and read the last integer that the pointer has past.

Reading 8 3 8 8

Energy usage is the difference between the two readings

8388 - 7129 = 1259 kWh

Reading an Energy Meter

1) Read initial digital value at start of period
2) Record value
3) Read final digital value at end of period
4) Subtract last reading from present meter reading
5) Difference is the usage in kWh for period

Reading an Electronic Energy Meter

Electric Load Characteristics

Large electric customers billed on energy and average power (demand)

Units for electric energy - kWh =kilowatt-hours

$$\text{Average power} = \frac{\text{Energy consumption over period}}{\text{Time period}}$$

Average Power = Demand

$$\text{Demand} = \frac{E_e}{T} = \frac{kWh}{hr} = kW$$

Demand meters compute and record demand on intervals of 15 min 30 min and 1 hour intervals automatically

Where: E_e = electric consumption
T = time period in hours

Electric Demand

Measuring instantaneous demand with electromechanical kWh meters

Instantaneous Demand = D_i

$$D_i = \frac{3.6 \times K_r \times K_h}{T} \quad kW$$

For Instrument transformer sites

$$D_i = \frac{3.6 \times K_r \times K_h \times (PTR) \times (CTR)}{T} \, kW$$

Where:

K_h = Watthour meter constant (Wh/rev located on meter face)
K_r = Number of revolutions / period
T = Total time (seconds)

An electromechanical watt-hour meter makes 10 revolutions in 15 seconds. (k_h = 7.2) Find the demand.

$$D_i = \frac{3.6 \times K_r \times K_h}{T} \quad kW$$

$$D_i = \frac{3.6 \times (10\,\text{rev}) \times (7.2\,\text{kWh/rev})}{15\,\text{sec}} \quad kW$$

D_i = 17.28 kW

As T decrease, D_i approaches the actual instantaneous power value. Increasing T and number of revolutions produces an average value of power demand over the time interval.

Electric Demand Calculation Example 7-7

End Lesson 7: Power and Energy Measurement

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