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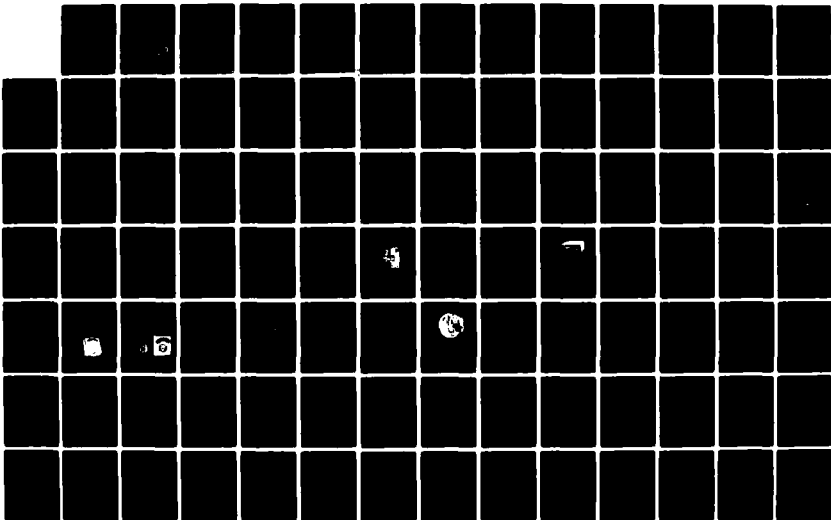
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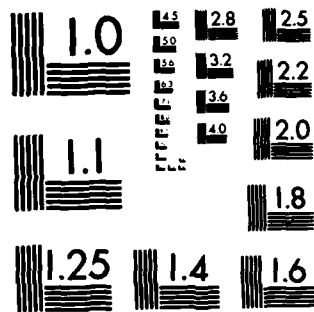
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MEASURING ACCURATELY SINGLE-PHASE SINUSOIDAL
AND NON-SINUSOIDAL POWER

by

George C. Laventure, Jr.

B.S.E.E., California State University at Sacramento, 1980

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirements for the degree of
Master of Science

Department of Electrical Engineering

1983

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ABSTRACT

The resulting effect of a significant increase in non-sinusoidal signals on power systems and equipment due to the application of new power electronic devices is a question yet to be answered. A subquestion in trying to determine the effects of non-sinusoidal signals on power systems and equipment is how to accurately measure these signals. This thesis makes an attempt to answer not only the question of how to measure accurately single-phase sinusoidal and non-sinusoidal power but also the question of which types of power and energy meters are most accurate and are less affected by these non-sinusoidal power variations. This thesis compares the accuracy of various power measurements using two General Electric Type P-3 Electrodynamometer wattmeters, two Clarke-Hess Model 255 Digital Wattmeters and one General Electric Type VM-63-S Induction Watthour Meter.

The experimental setup used to test the accuracy of the power and energy meters consisted of using a standard 120 V, 60 Hz single-phase source which feeds the power and energy meters. The power and energy meters were connected to the specific test source (either ac, half-wave rectified, or bidirectional thyristor-controlled) which was connected to the test load (high power-factor load, R-L load, or R-C load).

The results of the experimental work indicated that the P-3 wattmeters and the Clarke-Hess wattmeters measured accurately sinusoidal, non-sinusoidal and half-wave rectified power. The accuracy of the VM-63-S induction watthour meter is questionable as large variations in averaged power readings did occur.

This thesis for the Master of Science degree by

George C. Laventure, Jr.

has been approved for the

Department of

Electrical Engineering

by

Robert W. Erickson

William J. Hanna

Date _____

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Measuring Accurately Single-Phase Sinusoidal and Non-Sinusoidal
Power

Thesis Directed by Assistant Professor Robert W. Erickson

The advance of technology by the development of new power electronic devices for conversion, inversion, rectification and cycloconversion have resulted in more efficient ways of transforming and controlling power but at the same time have created a problem at times of inducing harmonic distortion and a dc component into the power system. The resulting effect of a significant increase in non-sinusoidal signals on power systems and equipment is a question yet to be answered.

A subquestion in trying to determine the effects of non-sinusoidal signals on power systems and equipment is how to accurately measure these signals. This thesis makes an attempt to answer not only the question of how to measure accurately single-phase sinusoidal and non-sinusoidal power but also the question of which types of power and energy meters are most accurate and are less affected by these non-sinusoidal power variations. This thesis compares the accuracy of various power measurements using two General Electric Type P-3 Electrodynamometer wattmeters, two Clarke-Hess Model 255 Digital Wattmeters and one General Electric Type VM-63-S Induction Watthour Meter.

The experimental setup used to test the accuracy of the power and energy meters consisted of using a standard 120 V, 60 Hz single-

phase source to feed the power and energy meters. The output of the meters was fed to the specific test source (either ac, half-wave rectified, or bidirectional thyristor-controlled) and from this source to the test load (high power-factor load, R-L load, or R-C load).

The results of the experimental work indicated that the P-3 wattmeters and the Clarke-Hess wattmeters measured accurately sinusoidal, non-sinusoidal and half-wave rectified (where a dc component is present) power. The accuracy of the VM-63-S induction watt-hour meter, based on the limited testing done in this thesis, is questionable as large variations in averaged power readings did occur.

ACKNOWLEDGEMENTS

I wish to express my appreciation to my thesis advisors, Dr. Robert Erickson and Professor William J. Hanna for the assistance and time given me in helping complete this thesis. I wish to thank Mr. Scott Striefert for assisting me with the ink drawings and I wish to thank the U.S. Air Force for providing me the opportunity and the financial support to complete this thesis work.

And lastly but not leastly, I wish to express my love and appreciation to my wife, Cathy, for her love and understanding and for just putting up with me during the trials and tribulations of completing this thesis work.

INTRODUCTION

As technology has progressed in the last 20 years, new methods using power electronic devices for conversion (dc to dc), inversion (dc to ac), rectification (ac to dc) and cycloconversion (ac to ac) have evolved. These new methods have resulted in more efficient ways of transforming and controlling power but at the same time have created a problem at times of inducing large harmonic distortion and a dc current component into the power system. The advance of technology by the development of these new power electronic devices has created the likelihood of power signals being non-sinusoidal. The resulting effect of a significant increase in non-sinusoidal signals on power systems and equipment is a question yet to be answered.

A subquestion in trying to determine the effects of non-sinusoidal signals on power systems and equipment is how to accurately measure these signals. Considering just the question of how to measure non-sinusoidal signals on power systems or more specifically, the question of how to accurately measure single-phase power and energy when non-sinusoidal or dc components are present is the concern of this thesis. The way of measuring single-phase power and energy is by the use of a power meter (wattmeter) or an energy meter (watthour meter). There are many different types of wattmeters and watthour meters available for measuring power and energy but their ability to measure non-sinusoidal power and energy accurately has not been sufficiently proven. Of particular concern to both the supplier and

the user of power is how the induction watthour meter will react to these non-sinusoidal signals, many of which contain a dc current component. Since the induction watthour meter is designed for measuring ac variations only, the creation of a dc component in an ac circuit due to thyristor-controlled sources or power-factor motor controllers has led to the question of whether an induction watthour meter is accurate enough to measure modern day power systems. The questions to be answered by this thesis are not only how to measure accurately single-phase sinusoidal and non-sinusoidal power but also which types of power and energy meters are most accurate and are less affected by these non-sinusoidal power variations. This thesis then is an attempt to compare the accuracy of power measurements using two General Electric Type P-3 Electro^{WATTMETERS}dynamometer~~s~~, two Clarke-Hess Model 255 Digital Wattmeters, and one General Electric Type VM-63-S Induction Watthour Meter. This thesis will also try to answer the question of whether the older analog wattmeters are more or less accurate in measuring sinusoidal and non-sinusoidal power than the modern digital wattmeters. Secondary objectives of this thesis are:

- a) to define the basic power definitions associated with sinusoidal power, non-sinusoidal power and power factor.
- b) to become familiar with and understand the basic operation of some of the different metering equipment available for measuring single-phase power and energy.
- c) to define measurement standards and types of measurement errors.
- c) to define the basic definitions for precision and accuracy, especially as applied to power measurements.

- e) to become familiar with and understand the specific operation of the Clarke-Hess digital wattmeter, the General Electric P-3 electrodynamic wattmeter, and the General Electric induction watt-hour meter.
- f) to become familiar with and understand the factors which affect the accuracy of the Clarke-Hess digital wattmeter, the General Electric P-3 electrodynamic wattmeter, and the General Electric induction watt-hour meter.
- g) to verify by experimental testing which types of meters give accurate measurement of sinusoidal and non-sinusoidal power.

This thesis work is broken down into three areas. Part I includes a discussion of the general background information uncovered during the literature search. It defines the basic power definitions of sinusoidal power, non-sinusoidal power and power factor. It defines the measurement standards and types of measurement errors that can occur when performing power measurements. It defines the basic definitions of precision and accuracy. Part I discusses different types of power and energy meters and treats specifically the operation of the P-3 electrodynamic wattmeter, the Model 255 digital wattmeter and the VM-63-S induction watt-hour meter. Part I concludes by discussing the factors which affect the accuracy of the P-3 wattmeter, the Model 255 wattmeter and the VM-63-S watt-hour meter. Part I fulfills the secondary objectives (a through f) of this thesis.

Part II covers the testing and experimental work performed. It discusses the pre-experimental analysis and the criteria used in determining the accuracy of the power measurement. It discusses the

various test sources (ac, half-wave rectified, and bidirectional thyristor-controlled) and the characteristics of the various test loads. Part II concludes by discussing the results obtained when measuring single-phase power using a sinusoidal source, a half-wave rectified source and a thyristor-controlled source with a high power-factor load, a R-L load and a R-C load. Part II fulfills the secondary objective (g) of this thesis.

Part III states the general conclusions drawn from this thesis work as well as summarizes the specific conclusions drawn from the experimental work done in Part II. Part III concludes by making some specific recommendations concerning the type of meter to use when making single-phase power measurements and by making some specific recommendations concerning possible additional research that can be done with regard to measuring single-phase non-sinusoidal power.

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PART I

General Background Information

CHAPTER 1

POWER, PERIODIC AND NON-PERIODIC FUNCTIONS

In order to understand how to measure sinusoidal or non-sinusoidal power, it is helpful to define the terminology associated with each. The following is an introduction of some of the basic terminology and theory relating to the measurement of power [1,2,3,4,5,6,7].

1.1 Power

Power is defined as the rate of change of energy with respect to time or the rate of doing work and can be expressed as

$$P = \frac{dw}{dt} = V \frac{dq}{dt} \quad (1.1)$$

The electrical unit of measurement for power is the watt, which is equivalent to one joule/second. Power (p) is considered to be an instantaneous quantity. If one is interested in measuring power over a specified time interval (e.g., for several periods), then the average power (P) may be computed by integrating the instantaneous power over this interval and the following results:

$$P = \frac{1}{nT} \int_{t_0}^{t_0+nT} p \, dT \quad (1.2)$$

where n is the integral number of periods, t_0 is the initial time, T is the time for one period and p is the instantaneous power. In practical applications, however, one is often interested in the energy

used and as a result watt-seconds or kilowatt-hours are measured. In my experimental work, I will be measuring both of these quantities.

1.2 Periodic and Non-Periodic Functions

Before defining sinusoidal and non-sinusoidal power, it is necessary to define periodic and non-periodic functions or waves [3, 4,5]. A periodic function is one that satisfies the equation

$$f(t) = f(t+nT) \quad (1.3)$$

for all values of t , where n is an integer and T is the period. Basically, a periodic function is one that repeats itself during each period of time; an example of a periodic function would be a sine-wave or the waveform shown in figure 1.1. NOTE: For my experimental work all voltage and current (power) waves were periodic.

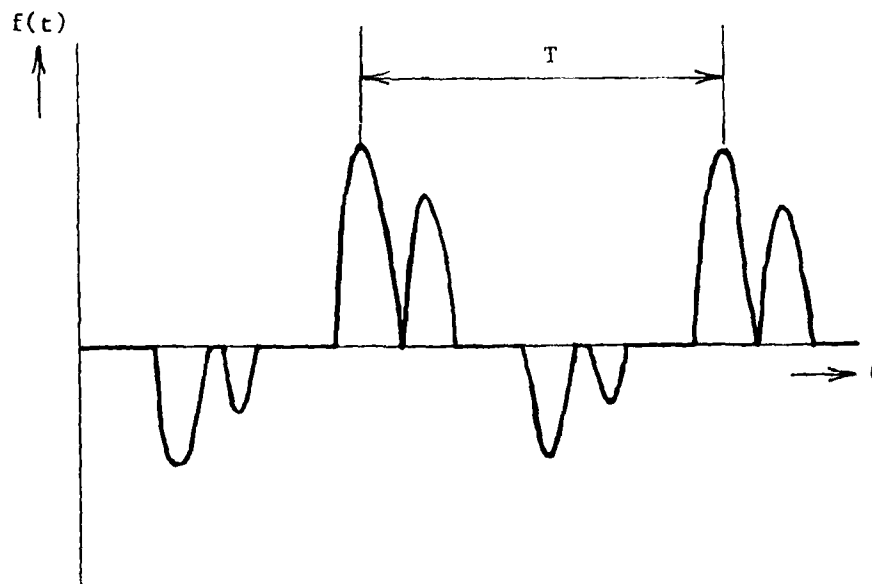


Figure 1.1 Periodic Waveform

A non-periodic function or wave is one that does not satisfy equation 1.3 and is basically non-repetitive in nature. An example of a non-periodic function would be random noise or the waveform shown in figure 1.2.

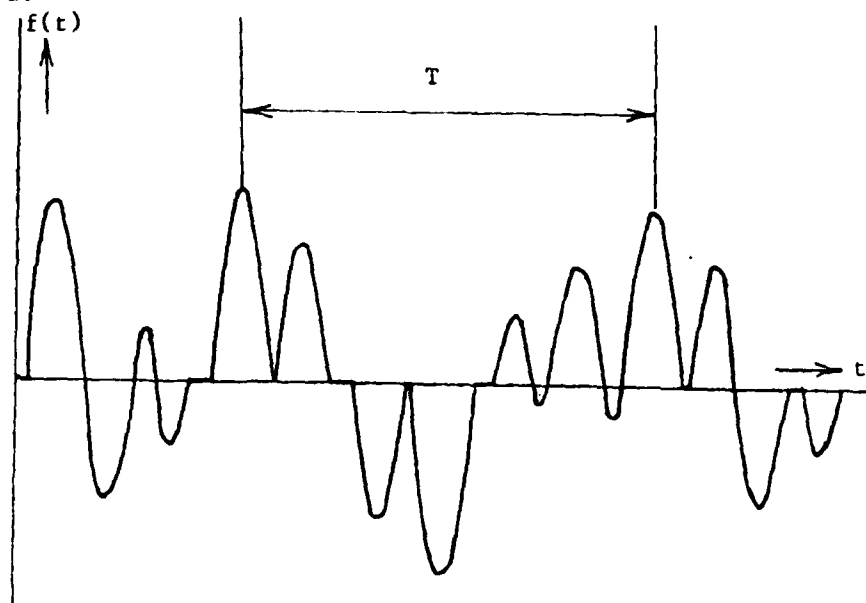


Figure 1.2 Non-periodic Waveform

Most power applications involve the use of periodic current and voltage waves; these waves may be sinusoidal or non-sinusoidal. I will next define sinusoidal and non-sinusoidal power and some related theory for each.

CHAPTER 2

SINUSOIDAL POWER, NONSINUSOIDAL POWER AND POWER FACTOR THEORY

2.1 Sinusoidal Power

Sinusoidal power is power that is a function of a sinusoidal voltage and/or current being impressed across and/or passing through a power dissipating element. The term sinusoid comes from the relationship that exists when a conductor is rotated in a magnetic field. The rotation of the conductor in a magnetic field results in an induced electromotive force (emf) which is directly proportional to the sine of the angle through which the conductor has rotated from the reference axis (reference figure 2.1).

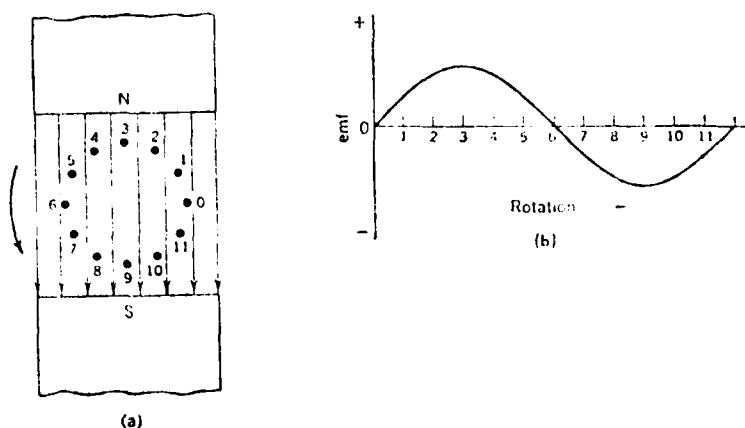


Figure 2.1 Nature of the induced emf.

Source: Herbert W. Jackson, Introduction to Electric Circuits (New Jersey: Prentice-Hall, 1965) p. 282

If the variations in alternating emf are plotted as in figure 2.1, the resulting graph is termed a sine curve. The alternating emf that varies in accordance with the sine curve is called a sine wave. The power resulting from a sine-wave voltage and/or current is sinusoidal power. Sinusoidal power then is a function of forcing functions or emf's that are sinusoidal in nature.

In order to define power in alternating circuits, it is necessary to define what is meant by real or average power, reactive power and apparent power.

The real or average power (also referred to as true power) is defined as the equivalent dc power delivered by an alternating source or the equivalent dc power dissipated by a pure resistance. This relationship is based on figure 2.2 where the heat dissipated by the resistance for the dc source is compared to the heat dissipated by the resistance for the ac source. When the temperature measured with the ac source is the same as the dc source, then the average electrical power delivered to the resistor by the ac source is the same as that delivered by the dc source.

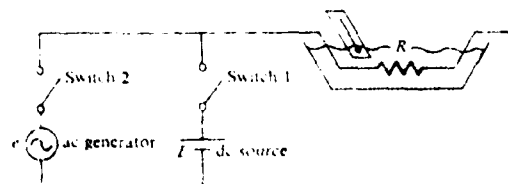


Figure 2.2 Power Measuring Test Set-up

Source: Robert L. Boylestad, Introductory Circuit Analysis (Ohio: Charles E. Merrill, 1977) p. 331

In sinusoidal ac power applications the instantaneous power delivered by an ac supply is given by

$$p = vi \quad (2.1)$$

If a general case is considered where

$$v = V_m \sin (\omega t + A) \quad (2.2)$$

$$i = I_m \sin (\omega t + B) \quad (2.3)$$

then

$$p = V_m I_m \sin (\omega t + A) \sin (\omega t + B) \quad (2.4)$$

using the trigonometric identity

$$\sin X \sin Y = \frac{\cos(X-Y) - \cos(X+Y)}{2} \quad (2.5)$$

then

$$p = \frac{V_m I_m}{2} \cos(A-B) - \frac{V_m I_m}{2} \cos(2\omega t + A+B) \quad (2.6)$$

The plot of current, voltage and power is shown in figure 2.3.

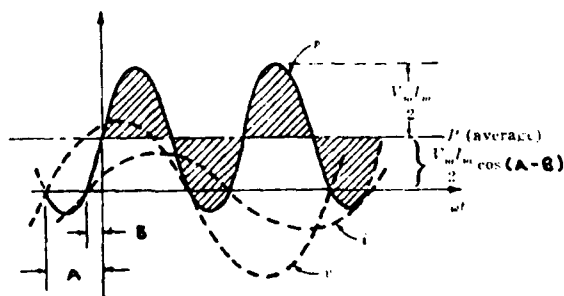


Figure 2.3. Current, Voltage and Power Waveforms for the General Case.

Source: Robert L. Boylestad, Introductory Circuit Analysis (Ohio: Charles E. Merrill, 1968) p. 309.

Note that the second factor in equation (2.6) is a cosine wave with an amplitude of $V_m I_m / 2$, and a frequency twice that of the voltage or current. The average value of this term is zero, producing no net transfer of power. The first term in equation (2.6) has a constant magnitude (no time dependence), and therefore could result in some net transfer of power. This first term is defined as the Average power (P) and is measured in watts (W) or kilowatts (KW). The angle (A-B) is the phase angle (θ) between v and i. Since $\cos(-\theta) = \cos(\theta)$ the magnitude of the average power is independent of whether v leads or lags i. The average power for equation (2.6) can now be rewritten as

$$p = \frac{V_m I_m}{2} \cos \theta \quad (2.7)$$

or as

$$P = V_{\text{eff}} I_{\text{eff}} \cos \theta = |V| |I| \cos \theta \quad (2.8)$$

The Apparent power of a system which applies to above general case, is defined by the product $V_{\text{eff}} I_{\text{eff}}$ or $V_m I_m / 2$ and is measured in volt-amperes (VA) or kilowatt-amperes (KVA). Its symbol is P_a . The apparent power can be expressed as

$$P_a = V_{\text{eff}} I_{\text{eff}} = |V| |I| \quad (2.9)$$

Another terminology associated with apparent power is Complex power (S). Complex power is defined as VI^* ; where I^* is the conjugate of I. For an example, if

$$v = |V| e^{j\omega t} \quad (2.10)$$

$$I = |V|e^{j\omega t} \quad (2.11)$$

then $I^* = |I|e^{-j\omega t} \quad (2.12)$

and the complex power could be defined as

$$S = VI^* = |V||I|e^{j(\omega t - \omega t)} = |V||I|e^{j\theta} \quad (2.13)$$

or

$$S = |V||I| (\cos \theta + j \sin \theta) = P + jQ \quad (2.14)$$

The magnitude of the complex power $|S|$ is also referred to as the Apparent power and can be expressed as

$$|S| = |VI^*| = |V||I| = \sqrt{P^2 + Q^2} = P_a \quad (2.15)$$

The reactive power of a system which applies to the above general case is defined by the product $V_{\text{eff}} I_{\text{eff}} \sin \theta$ and is measured in volt-amperes-reactive (VAR) or kilovar (KVAR). Its symbol is Q . The reactive power can be expressed as

$$Q = |V||I| \sin \theta = |S| \sin \theta \quad (2.16)$$

Considering next some of the basic linear components used in ac power applications, the instantaneous power can be defined as follows:

Rewriting equation (2.6)

$$p = VI \cos (A-B) - VI \cos (2\omega t + A+B) \quad (2.17)$$

a) In a purely resistive circuit,

$$P_R = |V||I| = |I|^2 R = \frac{|V|^2}{R} \quad (2.18)$$

and the resulting voltage, current and power waves are shown in figure 2.4.

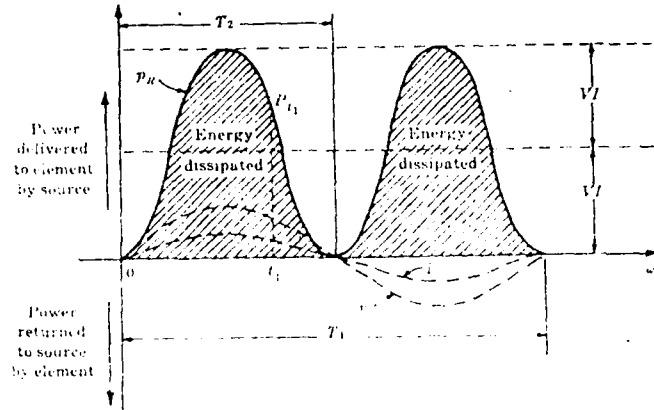


Figure 2.4 Voltage, Current and Power Waveforms for Purely Resistive Circuit

Source: Robert L. Boylestad, Introductory Circuit Analysis (Ohio: Charles E. Merrill, 1968) p. 434.

b) In a purely inductive circuit,

$$P_L = -VI \cos(2\omega t + A + B) \quad (2.19)$$

and the resulting voltage, current and power waves are shown in figure 2.5.

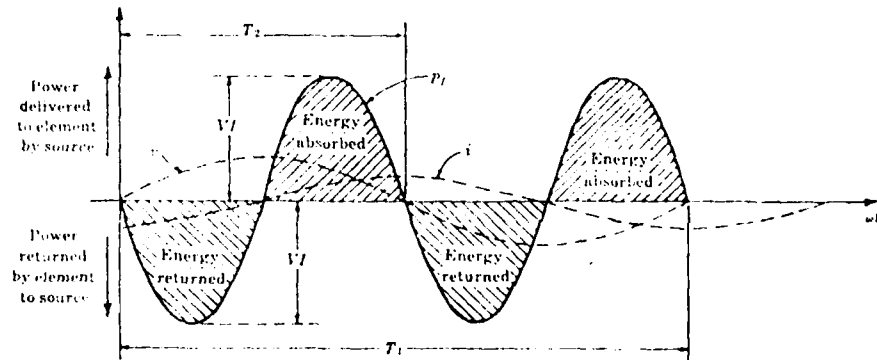


Figure 2.5 Voltage, Current and Power Waveforms for Purely Inductive Circuit

Source: Robert L. Boylestad, Introductory Circuit Analysis (Ohio: Charles E. Merrill, 1968) p. 437.

and

c) In a purely capacitive circuit,

$$P_C = VI \cos (2\omega t + A + B) \quad (2.20)$$

and the resulting voltage, current and power waves are shown in figure 2.6.

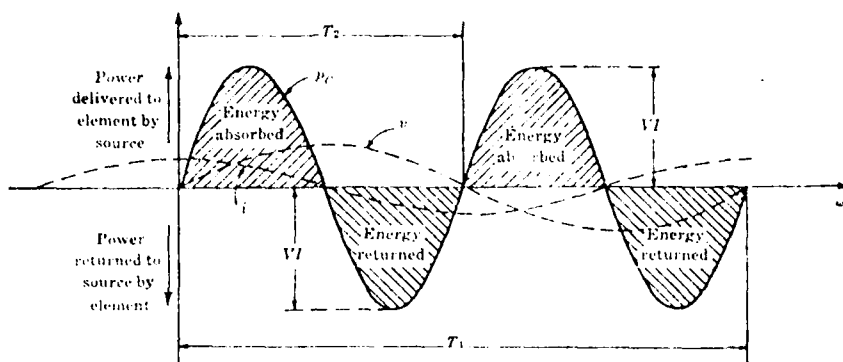


Figure 2.6 Voltage, Current and Power Waveforms for Purely Capacitive Circuit

Source: Robert L. Boylestad, Introductory Circuit Analysis (Ohio: Charles E. Merrill, 1968) p. 439.

In my experimental work in Part II of this report, resistive (R), resistive-inductive (RL) and resistive-capacitive (RC) networks are used. The resulting waveforms occurring under these conditions would be between the extremes above, and look something like figure 2.3.

2.2 Non-sinusoidal Power

Any waveform that differs from the basic definition of the sinusoidal waveform is referred to as nonsinusoidal [1,2,3]. A

periodic nonsinusoidal waveform is one that is repetitive in time and nonsinusoidal in form. A periodic nonsinusoidal wave of current passing through a resistor results in a power which is determined by the effective or rms value of the wave. This average power can be found by direct metering, by graphical analysis using the method of integration of the instantaneous power (the product of v and i), by determining the harmonic content of the nonsinusoidal wave and applying Fourier analysis, and by a method based on the principle of reciprocity. The direct metering method and graphical analysis will be used in my thesis work. The accuracy of direct metering using an analog, a digital, and a watt-hour meter will be compared with each other and compared with the solution obtained by graphical analysis and reported on in Part II. The method of calculating average power using waveform synthesis is applied when using the principle of reciprocity and Fourier analysis. Waveform synthesis is combining the parts of a wave so as to form the entire complex wave. In order to determine the average power in ac circuits with nonsinusoidal waveforms using waveform synthesis, the fundamental frequency, which harmonics are present, their relative amplitudes and their phase relationships with respect to the fundamental must be known. The principle of reciprocity is used in the Hammond electronic organ to duplicate the tone quality of various musical instruments and is based on the principle that an exact duplicate of a given nonsinusoidal wave can be obtained by adding together certain harmonically related sine waves with proper magnitudes and phase relationships. Fourier analysis is used in power analysis by recombining the terms of a

trigonometric series to form the complex waveform [2,4,5,8,9]. Fourier analysis can be applied to either a linear or nonlinear network.

In the case of a linear network such as a resistive or a series resistive-inductive (RL) network, with a nonsinusoidal waveform applied, the principle of superposition can be used as shown in figure 2.7.

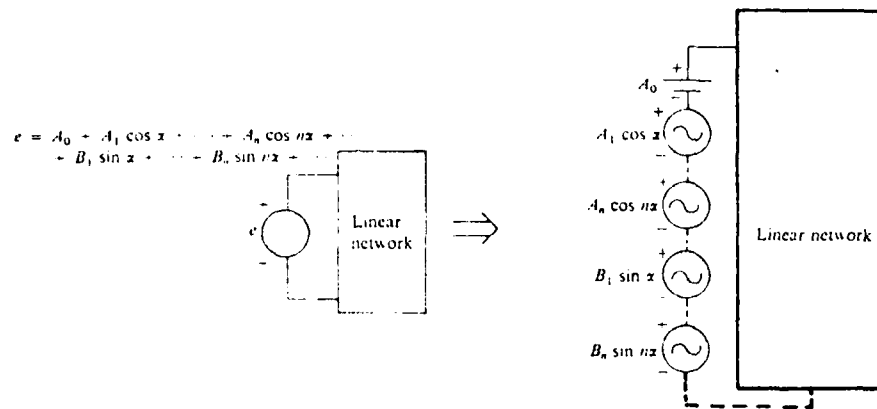


Figure 2.7 Applying Principle of Superposition to Linear Network

Source: Robert L. Boylestad, Introductory Circuit Analysis (Ohio: Charles E. Merrill, 1977) p. 617.

By breaking the input signal down into a series of sources and looking at the effect of each source independently on the linear network, the total response of the system becomes the algebraic sum of the Fourier series.

Before using the Fourier series, it is necessary to define the effective value of a waveform. For the test set-up shown in figure 2.2, the effective value of the current derived from the experiment is given by:

$$I_{\text{eff}} = \sqrt{\frac{\int_0^T [i(t)]^2 dt}{T}} \quad (2.21)$$

Equation (2.21) states that in order to find the effective value (I_{eff}), the function $i(t)$ must first be squared. After squaring $i(t)$ and plotting, the area under the curve is found by integration. This area is then divided by the period (T) to obtain the average or mean value of the squared waveform. The final step is to take the square root of the mean value. The square root of the mean value is the effective value or "root-mean-square (rms) value." The general expression for the effective value of any waveform from a mathematical analysis is given by:

$$F_{\text{eff}} = \sqrt{\frac{1}{T} \int_0^T [f(t)]^2 dt} \quad (2.22)$$

Applying this general equation to the following Fourier series:

$$\begin{aligned} v(\omega t) = & V_0 + V_1 \cos \omega t + \dots + V_n \cos n\omega t \\ & + V_1' \sin \omega t + \dots + V_n' \sin n\omega t \end{aligned} \quad (2.23)$$

yields

$$V_{\text{eff}} = \sqrt{\frac{1}{T} \int_0^T [v(\omega t)]^2 dt} \quad (2.24)$$

which after performing the indicated operations yields

$$V_{\text{eff}} = \sqrt{\frac{V_0^2 + V_1^2 + \dots + V_n^2 + V_1'^2 + \dots + V_n'^2}{2}} \quad (2.25)$$

and since

$$\frac{V_1^2}{2} = \left(\frac{V_1}{\sqrt{2}}\right)\left(\frac{V_1}{\sqrt{2}}\right) = V_1^2(\text{eff}) \quad (2.26)$$

then

$$V_{\text{eff}} = \sqrt{V_0^2 + V_1^2(\text{eff}) + \dots + V_n^2(\text{eff}) + V_1'^2(\text{eff}) + \dots + V_1'^2(\text{eff})} \quad (2.27)$$

Similarly, for

$$i(\omega t) = I_0 + I_1 \cos \omega t + \dots + I_n \cos n\omega t \\ + I_1' \sin \omega t + \dots + I_n' \sin n\omega t \quad (2.28)$$

then

$$I_{\text{eff}} = \sqrt{I_0^2 + I_1^2(\text{eff}) + \dots + I_n^2(\text{eff}) + I_1'^2(\text{eff}) + \dots + I_n'^2(\text{eff})} \quad (2.29)$$

The total power delivered to a linear network is the sum of that delivered by the corresponding terms of the voltage and current. In the following equations, all voltages and currents are effective values:

$$P_T = V_0 I_0 + V_1 I_1 \cos \theta_1 + \dots + V_n I_n \cos \theta_n + \dots \quad (2.30)$$

$$P_T = I_0^2 R + I_1^2 R + \dots + I_n^2 R + \dots \quad (2.31)$$

$$P_T = I_{\text{eff}}^2 R = V_{\text{eff}}^2 / R \quad (2.32)$$

In the case of a nonlinear network such as an ideal half-wave rectifier as shown in figure 2.7, the impedance of the circuit does not remain constant throughout the sine wave voltage and current waveforms. The rectifier is a nonlinear device and causes harmonics not contained in the input waveform to be generated. As a result, superposition cannot be applied to the input and it becomes necessary to know the total makeup of the source at the output of the diode. By examination of the waveform of figure 2.7, it can be seen that the

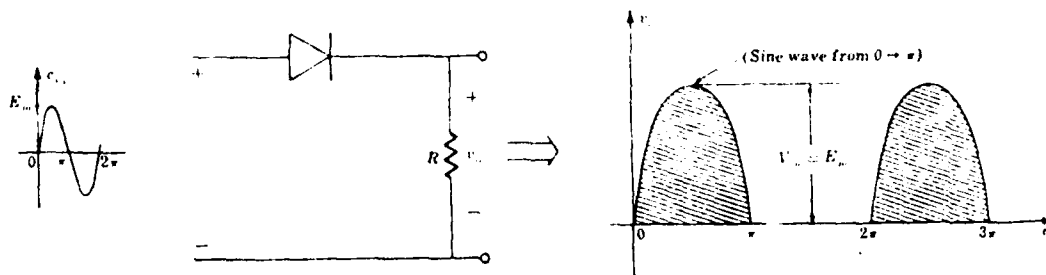


Figure 2.7 Ideal Half-Wave Rectifier Circuit and Waveform

Source: Robert L. Boylestad, Introductory Circuit Analysis (Ohio: Charles E. Merrill, 1968) p. 532

average value of the voltage waveform over a complete cycle is not zero. This is an indication that a dc component is present in addition to the harmonically related sine waves. The Fourier equation for the voltage wave of an ideal half-wave rectifier is

$$v_o = 0.318 V_m + 0.500 V_m \sin \omega t - 0.212 V_m \cos 2\omega t - 0.4024 V_m \cos 4\omega t - \dots - \frac{2V_m \cos n\omega t}{n^2 - 1} \quad (2.33)$$

where n is an even number and V_m is the maximum voltage across the resistor. The total power delivered to this nonlinear network can be calculated by equations 2.30 through 2.32. This nonlinear diode-resistor circuit will be used in the testing in Part II of this report.

Generally speaking, for either linear or nonlinear networks the average power can be expressed as the sum of the dc power (P_{dc}), the fundamental ac power (P_F) and the sum of the total harmonic power (P_H) [10, 11].

where

$$\text{Total Power} = E_{dc} I_{dc} + E_F I_F \cos \theta_F + E_H I_H \cos \theta_H \quad (2.34)$$

or

$$P_T = P_{dc} + P_F + P_H \quad (2.35)$$

It is important to note that only voltage and power at the same frequency combine to produce average power, and that the sign of the harmonic power term depends upon the power's point of origin in the network. This harmonic power term is of interest because the commercial induction watt-hour meter used to measure the energy used by the customer will measure in error based on the direction of the harmonic power flow. If the harmonics are being injected into the network by the supplier a negative registration error should occur in an induction watt-hour meter and the result should be a reduction in the customer's bill; if on the other hand the harmonics are being caused due to a nonlinear impedance or network at the customer's end, a positive registration error should occur in an induction watt-hour meter and the result should be an increase in the customer's bill.

The following discussion on apparent and reactive non-sinusoidal power is included for completeness of the subject area but is not central to my thesis. It does, however, indicate the complexity of trying to define apparent and reactive non-sinusoidal power and shows that serious disagreement exists between experts [12,13,14] on how to define these quantities. In the articles [12, 13] by Shepherd and Zakikhani apparent power is defined as

$$S^2 = \frac{1}{T_c} \int_0^{T_c} c^2 dt \cdot \frac{1}{T_i} \int_0^{T_i} i^2 dt = S_R^2 + S_X^2 + S_D^2 \quad (2.36)$$

where

S_R = active apparent power

S_X = true apparent power

S_D = apparent distortion power

The above definitions are classified by defining that portion of the apparent power due to active current (I_R) as apparent active power (S_R), the portion caused by reactive current (I_X) as apparent reactive power (S_X) and that additional portion of apparent power present with nonlinear loads as apparent distortion power (S_D). The authors never define reactive power but they do disagree with the definition of reactive power given by V.N. Nedelcu

where

$$Q = \sum_1^n E_n I_n \sin \theta_n \quad (2.37)$$

Also the article [14] by Sharon takes slightly a different approach than either Nedelcu or Shepherd and Zakikhani and defines apparent power (S'_X or S) as being made up of the quadrature reactive power (S_Q) and a complementary reactive power (S_C)

where

$$S'_X = \left[\left(\sum_1^n v_n^2 + \sum_1^m v_m^2 \right) \left(\sum_1^n I_n^2 \sin^2 \phi_n + \text{negligible terms} \right) \right]^{1/2} \quad (2.38)$$

and

$$S_Q = v_{rms} \left(\sum_1^n I_n^2 \sin^2 \phi_n \right)^{1/2} \quad (2.39)$$

$$S_C = \left[\sum_1^m v_m^2 \sum_1^n I_n^2 \cos^2 \phi_n + v_{rms}^2 \sum_1^p I_p^2 + 1/2 \sum_1^b \sum_1^\gamma (v_b I_\gamma \cos \phi_\gamma - v_\gamma I_b \cos \phi_b)^2 \right]^{1/2} \quad (2.40)$$

The above equations simplified give the following equations for apparent power

$$S = (P^2 + S_Q^2 + S_C^2)^{1/2} \quad (2.41)$$

which compares with the 1929 definition of apparent power in a non-linear system given by

$$S = (P^2 + Q^2 + D^2)^{1/2} \quad (2.42)$$

where P is the average power, Q is the reactive power and D is the distortion power.

2.3 Power Factor

The power factor of a circuit is universally defined as the ratio of the average power in watts to the apparent power in voltamperes, where

$$\text{Power Factor (P.F.)} = \frac{\text{Average Power}}{\text{Apparent Power}} = \frac{P}{Pa} \quad (2.43)$$

This definition of power factor is independent of frequency and waveform and applies to both sinusoidal and nonsinusoidal power. The actual meaning of power factor is relative to the type of power under consideration.

In the case of sinusoidal power, the power factor angle (θ) is defined as the phase difference between the voltage and current in a system, where

$$\theta = \angle V - \angle I \quad (2.44)$$

This phase angle indicates how close the load is near to being effectively resistive or how close the load is near to unity power factor. The power factor is expressed in terms of the power factor angle where

$$\text{P.F.} = \cos \theta \quad (2.45)$$

At unity power factor ($\text{P.F.} = 1$, $\theta = 0$), maximum effective power transfer occurs, that is, the average power is equal to the apparent power. Power factor can further be classified as lagging power factor for inductive loads and leading power factor for capacitive loads. Based on the above, the $\cos \theta$ or power factor has real or recognizable meaning in sinusoidal power applications.

On the other hand in nonsinusoidal power applications the term power factor can take on various meanings and is not easily defined. Depending on the sampling time, the phase relationship between voltage and current could change from leading to lagging almost instantaneously depending on the applied signal or the nonlinearity of the load. Any attempt to associate the power factor with $\cos \theta$ leads to difficulty since there is no longer a single phase angle between voltage and current waveforms but a separate phase angle for each frequency component (reference equation 2.29). Power factor takes on a wide variety of definitions depending on application. For example, in a thyristor controlled resistive load, P.J. Gallagher and W. Shepherd in their articles [15, 16] have defined power factor as

$$\text{P.F.} = \sqrt{\text{per unit power}} = \sqrt{\text{Power (pu)}} \quad (2.46)$$

and in a single-phase series R-L circuit with load voltage controlled by symmetrical triggering the power factor is given by

$$\text{P.F.} = \sqrt{\text{Power (pu)}} \cdot \cos \theta \quad (2.47)$$

where

$$\theta = \tan^{-1} (\omega L/R) \quad (2.48)$$

also several authors [15, 16, 17] have defined power factor for non-sinusoidal applications in terms of a displacement factor and a distortion factor. Specifically in thyristor controlled circuits with sinusoidal supply voltage, the power factor is expressed as

$$\text{P.F.} = \frac{EI_1 \cos \theta_1}{EI} = \frac{I_1}{I} \cos \theta_1 \quad (2.49)$$

where the distortion factor I_1/I is largely due to load impedance nonlinearity and the displacement factor $\cos \theta_1$ is largely due to load reactance.

It was also observed in several articles covering passive-network compensation that power factor can take on many different definitions depending on type of compensation. Some of these formulas are given in table 2.1.

Generally speaking, power factor can take on a variety of definitions and meanings depending on applications and types of power signals used. For my experimental work power factor is not a critical measurement variable and is addressed here for general informational purposes only.

Table 2.1

Power Factor With Different Forms of Passive-Network Compensation Connected at Supply Terminals

Form of compensation	Power factor
Uncompensated	$\frac{P_L}{E \sqrt{I_{L1}^2 + \sum I_{Ln}^2}}$
Constant capacitance C	$\frac{P_L}{E \sqrt{I_{L1}^2 + \sum I_{Ln}^2 + E^2 \omega^2 C^2 - 2EI_{L1} \omega C \sin \phi_1}}$
Variable (optimum) capacitance $C = C_S = \frac{I_{L1} \sin \phi_1}{\omega E}$	$\frac{P_L}{E \sqrt{I_{L1}^2 \cos^2 \phi_1 + \sum I_{Ln}^2}}$
Constant resistance R	$\frac{P_L + E^2 R}{E \sqrt{I_{L1}^2 + \sum I_{Ln}^2 + \frac{E^2}{R^2} + \frac{2P_L}{R}}}$
Variable resistance $R = E^2 P_L$	$\frac{2P_L}{E \sqrt{I_{L1}^2 + \sum I_{Ln}^2 + \frac{3P_L^2}{E^2}}}$
Constant resistance R and constant capacitance C	$\frac{P_L + E^2 R}{E \sqrt{I_{L1}^2 + \sum I_{Ln}^2 + E^2 \omega^2 C^2 - 2EI_{L1} \omega C \sin \phi_1 + \frac{E^2}{R^2} + \frac{2P_L}{R}}}$
Constant resistance R and variable capacitance C _S	$\frac{P_L + E^2 R}{E \sqrt{I_{L1}^2 \cos^2 \phi_1 + \sum I_{Ln}^2 + \frac{E^2}{R^2} + \frac{2P_L}{R}}}$
Variable resistance $R = E^2 P_L$ and variable capacitance C _S	$\frac{2P_L}{E \sqrt{I_{L1}^2 \cos^2 \phi_1 + \sum I_{Ln}^2 + \frac{3P_L^2}{E^2}}}$

Adapted from W. Shepherd and P. Zakikhani, "Power Factor Compensation of Thyristor-Controlled Single-Phase Load," IEE Proceedings, Vol. 120, 1977, p. 246.

CHAPTER 3

GENERAL METERING EQUIPMENT AVAILABLE FOR MEASURING SINGLE-PHASE POWER AND ENERGY

There are numerous different types of meters available for measuring average power and energy. This chapter will list some of the various meters available and the basic principle of measurement used in each.

3.1 Power Measuring Meters

Instruments designed to measure the amount of average power consumed in a circuit are known as wattmeters [23,24,31]. Some of the various types of wattmeters available, their basic operating principle and their principle use will be described next.

(1) Electrodynamometer Wattmeter

The electro-dynamometer or dynamometer is a direct indicating wattmeter that measures the average power in a circuit by developing a torque which is proportional to the current in the fixed and moving coils which is proportional to the average power. This relationship for determining power can be expressed as follows:

$$P \propto T \propto i_1 i_2 \quad (3.1)$$

The dynamometer wattmeter has a high degree of accuracy (normally 0.25 percent of full scale in a precision instrument) and is used as a standard for both ac and dc power

measurements. The dynamometer is accurate for ac measurements with frequencies up to 125 Hz without special correction curves or special compensating networks. A problem may occur when using the dynamometer at low power factor due to the high inductance of the voltage coil. The electro-dynamometer is used to measure both sinusoidal and non-sinusoidal power.

(2) Iron-cored Dynamometer

The iron-cored dynamometer is a direct indicating wattmeter that measures the average power in a circuit by developing a torque which is proportional to the current in the current and moving coils which is proportional to the average power. This relationship for determining power can be expressed as follows:

$$P \propto T \propto i_1 i_2 \quad (3.2)$$

An interior view of an iron-cored dynamometer wattmeter movement is shown in figure 3.1.

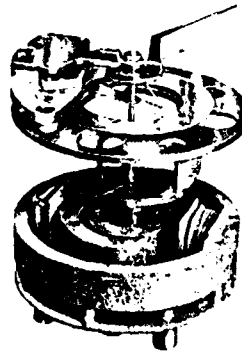


Figure 3.1 Interior View of Iron-cored Dynamometer
Wattmeter Movement

Source: W. Alexander, Instruments and Measurements (London: Cleaver-Hume Press LTD, 1962) p. 66

The use of the iron-cored dynamometer wattmeter is largely due to increasing use of circular-scale instruments; that is, instruments having scale arcs of the order of 240° . This instrument can only be used on ac of standard industrial frequencies and is of normal industrial grade accuracy (1.0 to 1.5 per cent of full scale). The use of an iron-core dynamometer for non-sinusoidal power measurements would not be recommended due to frequency and waveform errors and because the meter would not measure the dc component of power.

(3) Induction Wattmeter

The induction wattmeter is a direct indicating wattmeter which measures the average power in a circuit by developing a torque which is proportional to the current and voltage in the fixed voltage and current coils. This relationship for determining power can be expressed as:

$$P \propto T \propto i_1 i_2 \propto i_1 v_2 \quad (3.3)$$

The induction wattmeter has a high driving torque and is almost immune from effects due to stray fields. The induction wattmeter is of industrial grade accuracy and operates on ac circuits at stated calibration frequencies and temperatures. The use of an induction wattmeter for non-sinusoidal power measurements would not be recommended as errors could be introduced due to the dc component of power.

The induction wattmeter is essentially a watt-hour meter in which the moving part is restricted to give an indication of power by a control device instead of being free to rotate

continuously as in the energy meter.

(4) Electrostatic Wattmeter

The electrostatic (quadrant electrometer type) wattmeter is a direct indicating wattmeter which measures the average power in a circuit by developing a torque which is proportional to the average power absorbed by the load. The deflecting torque developed is proportional to the charges on the plates which is proportional to V_1V_2 . This relationship for determining power can be expressed as:

$$P \propto T \propto v_1v_2 \quad (3.4)$$

The electrostatic wattmeter has been built following the principle illustrated in figure 3.2 in which electrostatic forces resulting from the applied line potential and the IR drop across a resistance (R) provide the torque.

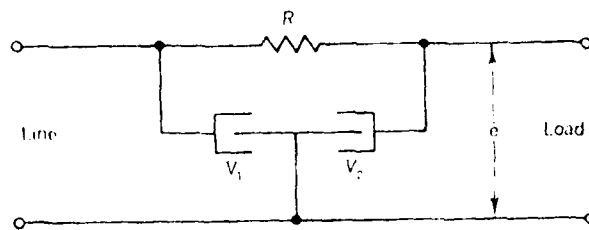


Figure 3.2 Electrostatic Wattmeter

Source: Walter Kidwell, Electrical Instruments and Measurements (New York: McGraw-Hill, 1969) p. 177.

The electrostatic wattmeter is a precision or laboratory wattmeter and normally would not be used for industrial

applications. It is used for the measurement of power of small magnitude and low power factor, and also when the voltage of the system is high.

(5) Electrothermic Wattmeters

An electrothermic wattmeter is a wattmeter made from a pair of matched thermoelements (see figure 3.3). Thermal wattmeter indications are derived from the temperature difference (created by current difference) between two heater elements. Heater currents i_1 and i_4 are functions of the voltage (e) across the load and the load current (i). If the circuit is symmetrical and the thermocouples matched, the voltages produced at the thermocouple junctions are identical if equal currents flow in the heaters. The thermocouples are connected in polarity so that they are opposing each other. When there is no load, the combined thermocouple output is zero. When power is consumed by the load, the additional current through P_1 unbalances the bridge and produces a resultant thermocouple voltage (V) which is proportional to the load power. This relationship for determining power can be expressed as

$$P \propto V^2 \quad (3.5)$$

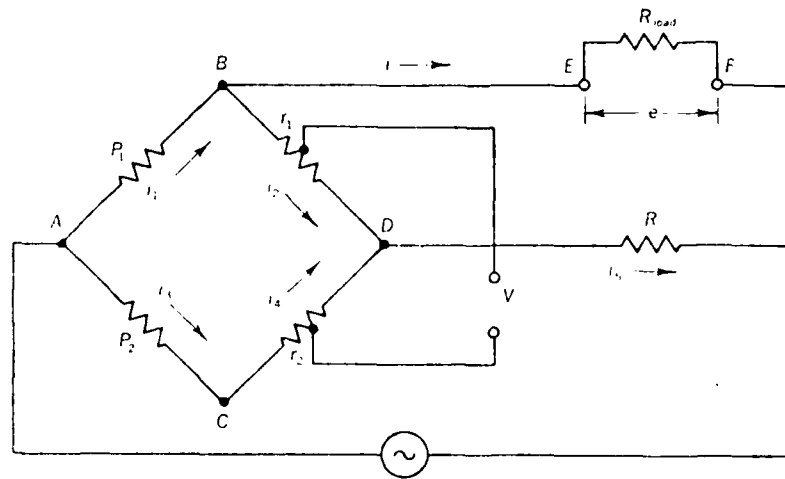


Figure 3.3 Electrothermic Wattmeter

Source: Walter Kidwell, Electrical Instruments and Measurements New York: McGraw-Hill, 1969) p. 178.

(6) Digital Wattmeters

A digital wattmeter such as the Clarke-Hess Model 255 is a modern electronic measuring device which takes the load voltage and current signals and multiplies them together to give an instantaneous power output. This instantaneous power output is fed through an output filtering network which converts the instantaneous power signal to an average power equivalent. This relationship for determining power can be expressed as:

$$P \propto iv \quad (3.6)$$

This average power equivalent is fed to an analog-to-digital (A/D) converter which is used to drive a counter/display network which displays the average power in its

equivalent numeric value.

A digital wattmeter can be used to measure both ac and dc sinusoidal and nonsinusoidal power. The accuracy of a digital wattmeter such as the Clarke-Hess Model 255 is dependent on frequency and power factor and is normally in the range ± 0.5 to 1.0 percent of full scale and $\pm 0.5\%$ of reading.

3.2 Energy Measuring Meters

Instruments designed to measure the amount of power consumed in a circuit in a given time interval are known as energy meters. Some of the various types of energy meters, their basic operating principle and their principle use will be discussed next.

(1) Clock Meter

The basis of this meter operation consists of a two-pendulum clock mechanism. Two sets of coils are energized, one set by the current passing to the load and the other by the supply voltage. The voltage coils are carried by the pendulums and are subjected to a magnetic pull on swinging past the fixed current coils. This interaction causes an accelerating force on one pendulum and a retarding force on the other, and the resulting difference in time period of oscillation of the two pendulums is arranged to give an indication on a dial register mechanism, proportional to the energy passing through the meter.

The clock mechanism is suitable for both ac and dc energy measurements but the mechanism is complicated and costly, and is now seldom used.

(2) Motor Meters

Motor meters are energy meters that work on the principle of motoring action. They have three main parts consisting of a driven rotating element (disk), a braking system, and a clock or dial register. The rotating element is driven at a speed proportional to the energy. Proportionality between the energy and speed is given by the braking system, which supplies a controlling action proportional to the speed of the rotor element. There is no damping system and the deflecting system now becomes a rotating system which is coupled to a geared mechanism which registers in kilowatt-hours.

There are two types of motor meters. The mercury motor meter (see figure 3.4) which is used for dc energy measurement and the induction meter (see figure 4.10) which is used for ac energy measurements. The mercury motor meter is essentially an ampere-hour type meter but can be calibrated to read kilowatt-hours since the supply voltage will normally remain constant. The ac induction watt-hour meter is used extensively in residential and industrial installations and is treated in great detail in Chapters 4 and 8.

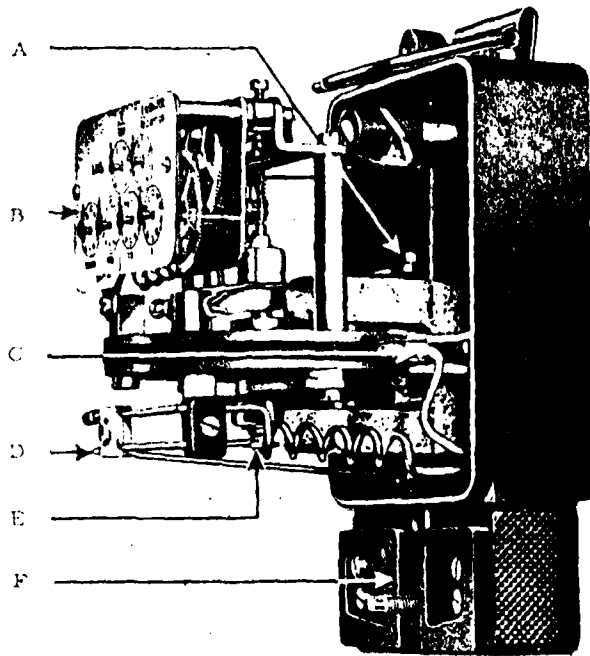


Figure 3.4 Mercury Motor Energy Meter

Source: W. Alexander, Instruments and Measurements
(London: Cleaver-Hume Press Ltd., 1962) p. 158

3.3 Conclusions

The meters to be used for the measurement of sinusoidal and non-sinusoidal power or energy for standard industrial applications are limited to the following types of meters: (a) electro-dynamometer, (b) digital wattmeters and (c) induction watt-hour meters. The electro-dynamometer and digital wattmeters are most accurate and operate effectively on both ac and dc power applications. The induction watt-hour meter is most commonly used to measure industrial energy usage and is subject to error when measuring non-sinusoidal power with high dc current and/or voltage components. For my experimental work, all three types of meters were used and the results are summarized in the conclusions of Part II.

CHAPTER 4

OPERATION OF SPECIFIC METERING EQUIPMENT USED FOR SINGLE-PHASE POWER AND ENERGY MEASUREMENTS

This chapter covers the operation of the power and energy meters that will be used in the testing phase of this thesis. It covers specifically the operation of the Clarke-Hess Model 255 Digital V-A-W Meter, the operation of the General Electric Type P-3 Electrodynamic Single-phase Wattmeter, and the operation of the General Electric Type VM-63-S Induction Watthour Meter. This chapter contains a discussion of the general characteristics of each measuring device such as its basic operation and frequency range. It covers the theory of operation for each meter and gives a short conclusion as to the accuracy and application of each.

4.1 Clarke-Hess Model 255 V-A-W Meter

General

The Clarke-Hess Model 255 V-A-W meter (see figure 4.1) measures average power and true rms voltage and current. These measurements are essentially independent of the waveshape or power factor from dc up to a frequency of 100 KHz. The internal wiring configuration of the Model 255 [20] is composed of six circuit boards (see figure 4.2) with the input controls being integrated on the Digital Control section. Electrically, the main printed circuit boards are the Analog section, the Digital Control section, and the Power Supply section. The three smaller printed circuit boards include the

Display/Counter and Latch section, the Current Attenuator board, and the Voltage Input board.

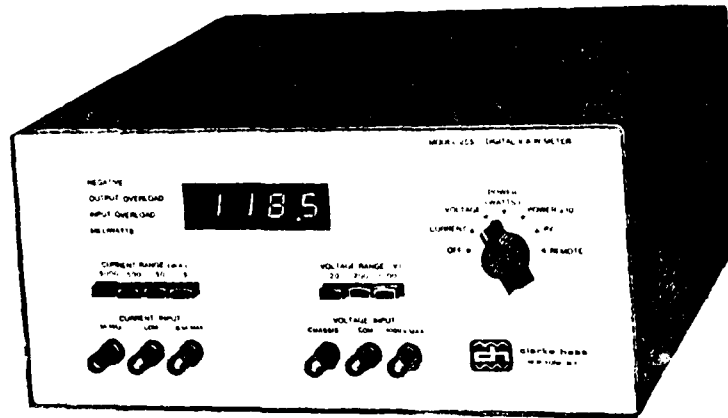


Figure 4.1 Clarke-Hess Model 255 Digital V-A-W Meter

Source: Clarke-Hess Corporation, Operation Manual for the Clarke-Hess Model 255 V-A-W Meter (New York: Clarke-Hess, 1980) Specifications

The basic operation of the Model 255 when used for power measurements is as follows: The input voltage and current signals are attenuated, frequency compensated, and amplified and sent to a multiplier network which combines both the instantaneous voltage and current to produce the instantaneous power at its output. Since this instantaneous power output is independent of waveform, the Model 255 measures dc, sinusoidal and non-sinusoidal power. This instantaneous power output is next fed through an output filtering network which converts the instantaneous power to an average power. The average power is then fed to an A/D converter which converts this average power to a BCD equivalent. This BCD equivalent is sent to the Display/Counter network which displays this average power in its equivalent numeric value. A more detailed explanation of this operation follows.

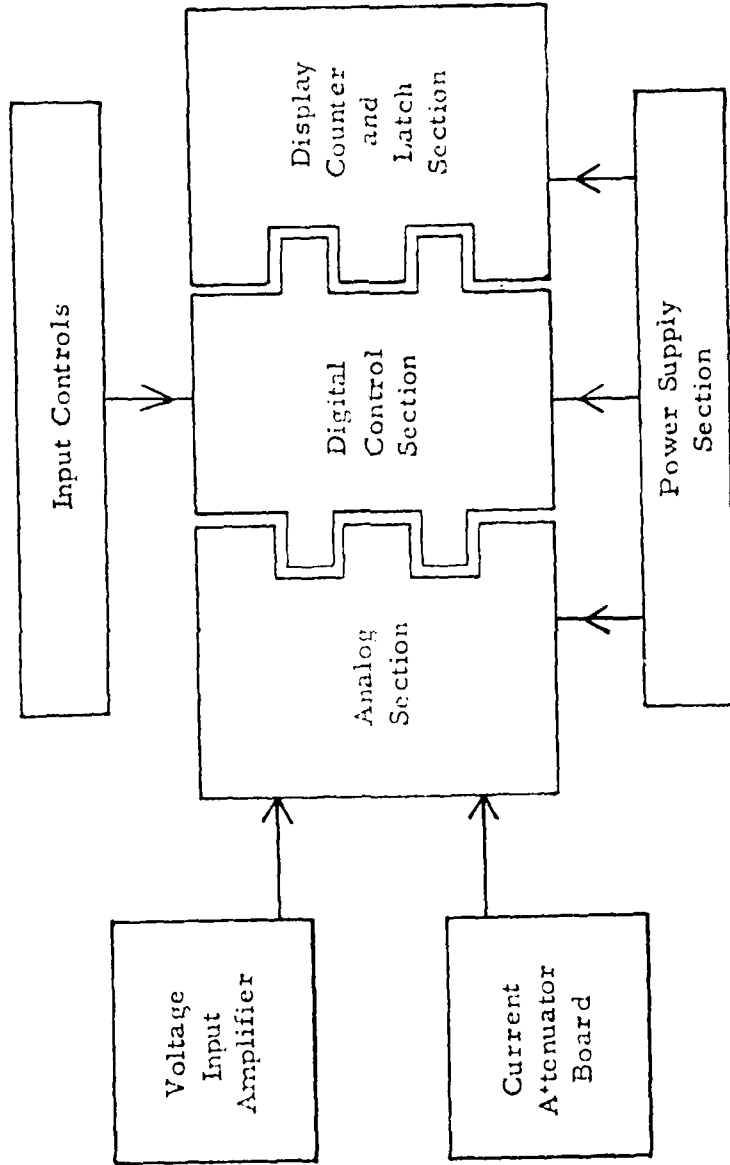


Figure 4.2 Breakdown of Model 255 V-A-W Meter Circuitry

Source: Clarke-Hess Corporation, Operation Manual for the Clarke-Hess Model 255 V-A-W Meter (New York: Clarke-Hess, 1980) p. III-2

Theory of Operation

The operation of the Clarke-less Model 255 when used to measure power is described as follows: The signals to be measured enter the V-A-W meter via the voltage and current input terminals (see figure 4.1 and figure 4.3). The voltage signal is attenuated and frequency compensated via a resistive-capacitive voltage divider network, and fed to a buffer network which converts the high impedance input to a low impedance output. The output of the buffer is then sent to the two stage voltage amplifier portion of the Analog section. This voltage output is then sent to the multiplier. During this time interval the same operation is occurring on the current signal. The current signal is converted to a voltage via the input resistance bridging network, attenuated and frequency compensated before being fed to the two stage current amplifier portion of the Analog section. Note: no buffer is needed for input impedance conversion as the bridging resistance is very low (30 milliohms to 20 ohms). This current (actually a voltage) output is then sent to the multiplier. The multiplier receives the two analog signal inputs together with *control inputs and produces the instantaneous product of the inputs (instantaneous power)*. After processing by the multiplier output circuitry, the low frequency (near dc) portion of this product is separated out by the output filter network giving an average power equivalent which is fed to the Analog to Digital (A/D) converter. The A/D conversion is accomplished by an Integrator/Comparator network together with a number of logic control circuits from the Digital section and the digital counters on the display board.

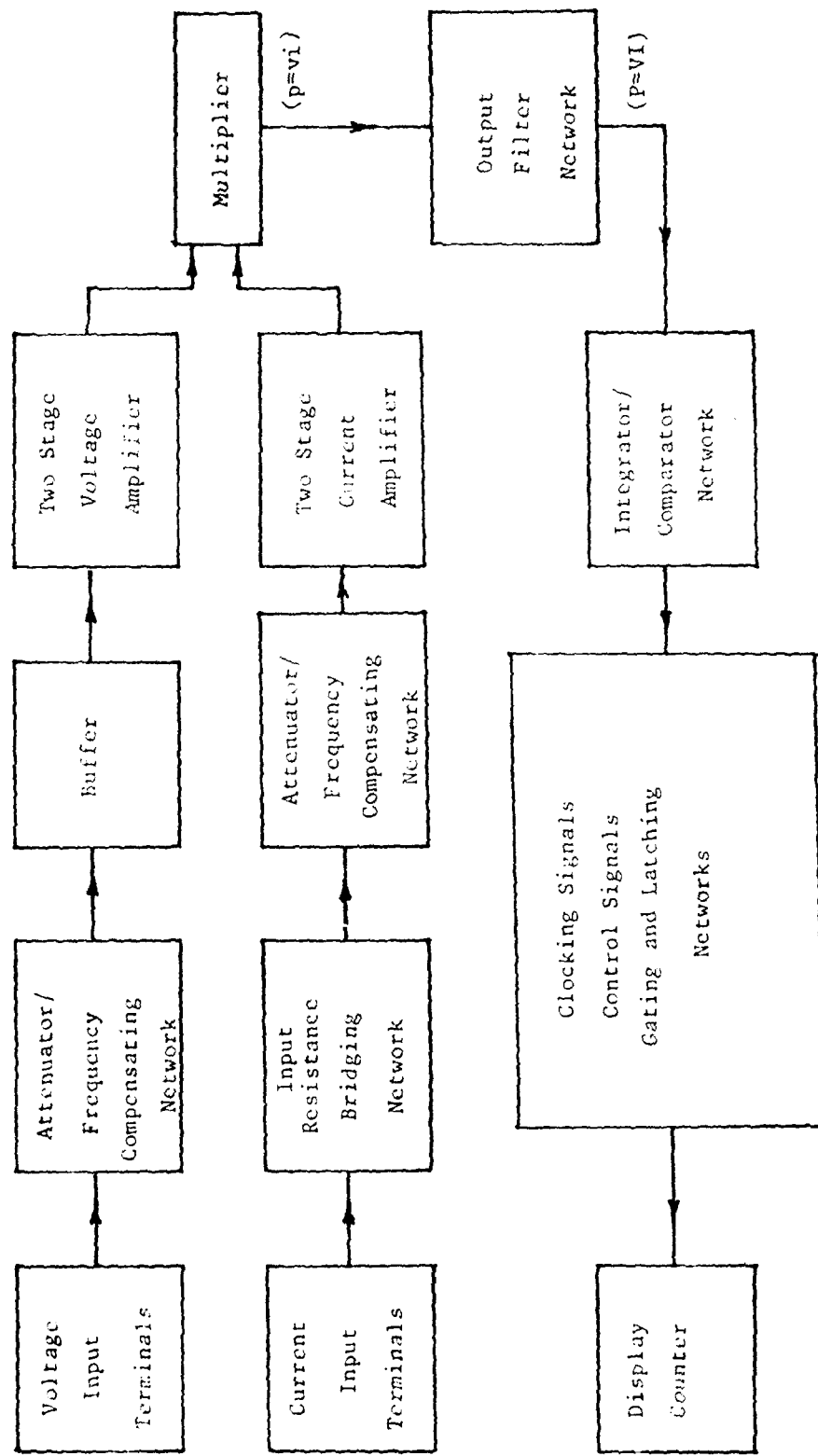


Figure 4.3 Added Block Diagram for Operation of Model 255 When Used for Power Measurement

The operation of the A/D converter is broken down into two periods (see figure 4.4), known as SIGNAL and REFERENCE.

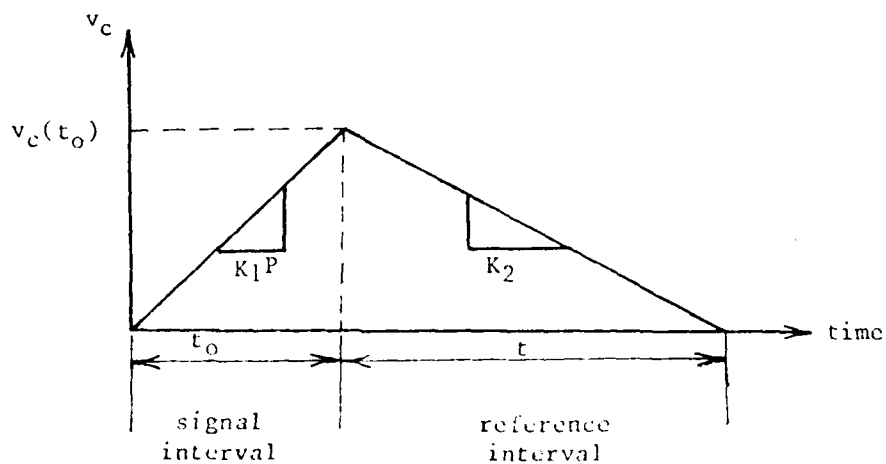


Figure 4.4 A/D Converter Operation Periods

During the SIGNAL period the output of the filter network is applied to the Integrator and a capacitor is charged during this 9.99 millisecond interval by a current equal to the output filter voltage divided by the integrator resistance. At the end of this SIGNAL period the output filter network is removed and a reference signal is applied to the integrator. The period from the time the reference signal is applied, which is the length of time necessary to completely discharge the capacitor back to zero, is known as the REFERENCE period. The end of the REFERENCE period is generated when the capacitor reaches zero volts which causes the Comparator to change states. It can be seen from figure 4.4 that the average power measurement is directly proportional to the output filter voltage applied during the SIGNAL

interval but is measured based on the decay time (t) of the REFERENCE interval. The output voltage at the end of the SIGNAL interval can be expressed as:

$$v_c(t_0) = K_1 P t_0 \quad (4.1)$$

and the output voltage at the beginning of the REFERENCE interval can be expressed as:

$$v_c(t_0) = K_2 t \quad (4.2)$$

By equating the SIGNAL and REFERENCE intervals

$$K_1 P t_0 = K_2 t \quad (4.3)$$

the following results:

$$t = \frac{K_1}{K_2} t_0 P \quad (4.4)$$

It can be seen that the average power (P) can be equated or is proportional to the time (t), where

$$t \propto K_3 P \quad (4.5)$$

This time period (t), which is a measure of the average power, is measured by the use of a digital counter network. The counter output is moved at the end of the REFERENCE period into the binary coded decimal (BCD) latches and into the digital display latches on the Display Counter Latch board. The actual value of the average power is then read directly from the display on the front of the Clarke-Hess meter.

Conclusion

Because of its ability to measure power instantaneously and independent of frequency or waveform variations, the Clarke-Hess Model 255 measures dc, sinusoidal and non-sinusoidal power up to a frequency of 100 KHZ. The accuracy of the Model 255 is specified as ± 0.4 per cent of full scale and ± 0.2 per cent of the reading.

4.2 General Electric Type P-3 Electrodynamic Wattmeter

General

The General Electric (G.E.) Type P-3 Wattmeter [21,22], is referred to as an electrodynamicometer or electrodynamic instrument and is often further shortened to "dynamometer." The G.E. Type P-3 Wattmeter is shown in figure 4.5.



Figure 4.5 General Electric Type P-3 Electrodynamic Wattmeter

Source: General Electric Manual of Electric Instruments, GET-1087A
(New York: General Electric, 1949) p. 47

The P-3 wattmeter measures average power and can be configured to measure true rms voltage and current. These measurements are essentially independent of the waveshape from dc up to 133 Hz. The effect of power factor and harmonic distortion is discussed under factors which affect the accuracy of the P-3 wattmeter in Chapter 7.

A typical cutaway view of a dynamometer mechanism is shown in figure 4.6 and a front view of the type P-3 dynamometer is shown in figure 4.7. The principle parts of a dynamometer mechanism are the frame, the field coils, the moving elements (shaft, the armature coil, the lead-in spirals), the control spring, the pointer, balance weights, the damping vane, the damping magnets, the jewel bearings, the scale, the pointer stops and the resistance spool.

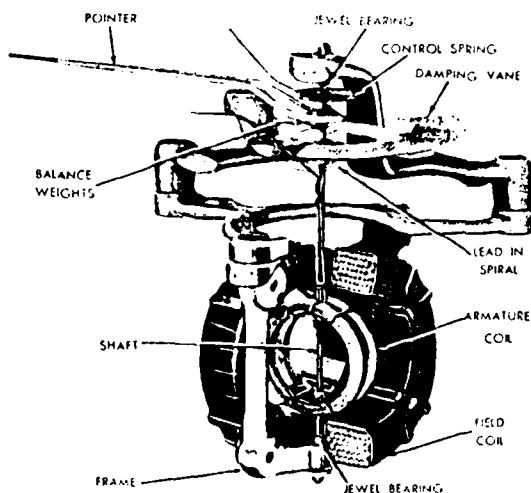


Figure 4.6 Cutaway View of a Dynamometer Mechanism

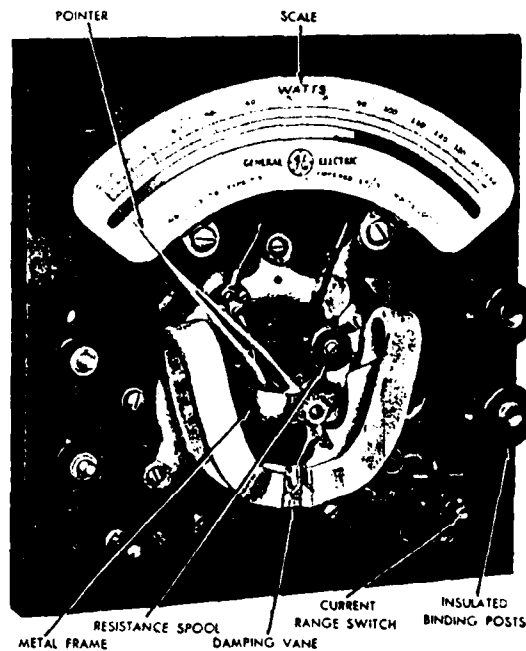


Figure 4.7 Front View of a G.E. Type P-3 Dynamometer

Source: General Electric, Manual of Electric Instruments, GET-1087A (New York: General Electric, 1949) p. 49 and p. 51.

The basic operation of the type P-3 wattmeter is as follows: the P-3 wattmeter is an instrument that measures power by means of the torque developed due to the changes in either field or armature current. Torque is proportional to the product of the field and armature current, where

$$T \propto i_1 i_2 \quad (4.6)$$

The dynamometer mechanism used as a wattmeter is shown in figure 4.8. This figure shows the field coil (stationary coil) of the mechanism connected in series with the line and the armature coil (moving coil) in series with a resistance connected across the line. Since the field flux is proportional to the line current (i_1) and the armature flux is proportional to the line voltage ($i_2 R$), the instantaneous torque is proportional to the instantaneous product of the line current and line voltage. This instantaneous torque is a measure of the instantaneous power. Because of its ability to measure power instantaneously and independent of frequency and waveform variations, the General Electric Type P-3 Wattmeter measures dc, sinusoidal and non-sinusoidal power up to a frequency of 133 Hz. The P-3 wattmeter is calibrated to read the average of the instantaneous power pulses or the real power of the network. A more detailed explanation of this operation follows.

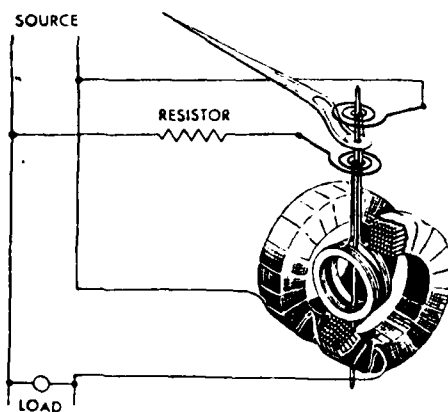


Figure 4.8 Dynamometer Mechanism Used as a Wattmeter

Source: General Electric, Manual of Electric Instruments, GET-1087A (New York: General Electric, 1949) p. 51.

Theory of Operation

The operation of the P-3 dynamometer when used as a wattmeter is as follows [21,23,24,25]: the dynamometer movement operates on the interaction of a fixed or stationary set of coils and a moving set of coils. This coil arrangement can be represented by figure 4.9, where the fixed coils (F_1 and F_2) are connected in series and the moving coils (M_1 and M_2) are connected in series. It should be noted that the P-3 wattmeter uses circular coils for the fixed and moving coils as they are more stable as to shape than the oval or flat-sided coils of earlier design. Also, the fixed and moving coils are two in number and have their planes parallel and a short distance apart. This

arrangement gives approximately a uniform magnetic field in the region between the coils.

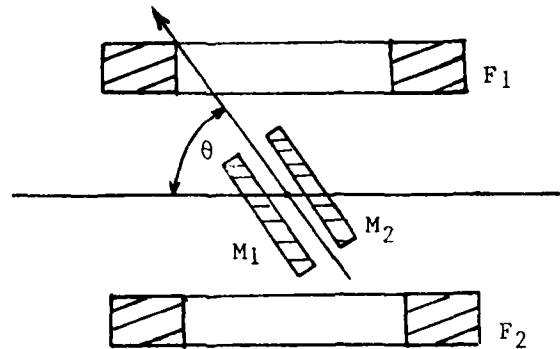


Figure 4.9 Plane View of Stationary and Moving Coils of an Electrodynamometer Mechanism

Source: C.T. Baldwin, Fundamentals of Electric Measurements, (New York: Frederick Ungar Publishing Co., 1961) p. 84

Considering figure 4.9, let currents i_1 and i_2 be the currents in amperes in the fixed and moving coils and let the plane of the moving coil in its resulting deflected position make an angle θ with the planes of the fixed coils. Let M be the mutual inductance between the coils in this position. Then the flux density of the field produced by the fixed coils is proportional to i_1 and the resulting force on the conductors of the moving coils for a given field strength is proportional to i_2 . Hence, the torque on the moving coil is proportional to the product of the currents in the coils and the rate of change of mutual inductance with respect to the deflection angle, or

$$T \propto i_1 i_2 \frac{\delta M}{\delta \theta} \quad (4.7)$$

The quantity $\delta M / \delta \theta$ is constant over a wide range of θ , so effectively the torque is proportional to $i_1 i_2$. Since the period of the moving coil system is much greater than the period of the input signals, the pointer assumes a position proportional to the average value of the power (P).

Conclusion

Because of its ability to measure power instantaneously and independent of frequency or waveform variations, the General Electric Type P-3 Wattmeter measures dc, sinusoidal and non-sinusoidal power up to a frequency of 133 Hz. The accuracy of the P-3 wattmeter is specified as ± 0.2 per cent of full scale value.

4.3 General Electric Type VM-63-S Induction Watthour Meter

General

The General Electric Type VM-63-S is a polyphase induction watthour meter. For my experimental work, I have modified this meter for single-phase power measurement by connecting the current coils in series and the voltage coils in parallel. The VM-63-S watthour meter is being used because of unavailability of a single-phase watthour meter that has contacts available for sensing the number of disk revolutions. The number of disk revolutions will be counted, averaged and compared to the average power measured by the Clarke-Hess digital wattmeter and the General Electric electrodynamicometer wattmeter. The General Electric Type VM-63-S meter is similar in construction to the V-64-S meter [26] shown in figure 4.10.

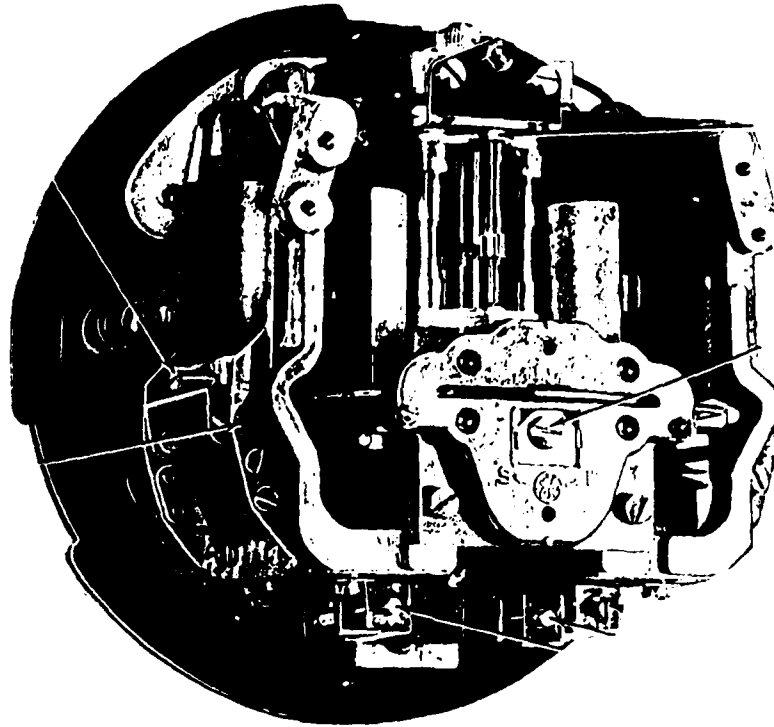


Figure 4.10 View of Internal Construction of the General Electric Type V-64-S Induction Watthour Meter

Source: General Electric, How to Test and Adjust General Electric AC Watthour Meters, GET-813G, (New York: General Electric, 1964) p.13

The General Electric Type VM-63-S induction watthour meter is an energy meter. It differs from a wattmeter in that a wattmeter measures the instantaneous power or rate of electricity utilization; whereas, the induction watthour meter integrates all of the instantaneous power values so that the total energy utilized over a period of time is known. If one is able to hold a load relatively constant over a period of time, the energy used can be converted to an average power and compared to the average wattmeter reading for this same time interval. This method is used in Part II of this thesis.

The General Electric induction watthour meter, whether single phase or polyphase, measures the energy used over a period of time. The energy measurement is not independent of the waveshape and the induction watthour meter is calibrated normally to operate on 50 or 60 Hz sinusoidal signals. Because the induction watthour meter is not independent of waveform or frequency variations, the use of this meter for measuring non-sinusoidal power, especially when a large dc component is present is questionable. The effects of power factor and harmonic distortion on the induction watthour meter are discussed under factors which affect the accuracy of the induction watthour meter in Chapter 8.

The principle parts of a single-phase induction watthour meter are shown in figure 4.11 . The main parts are the electromagnetic elements (voltage and current coils), the magnetic braking system, the moving elements (guide and disk), and the register.

The principle parts of a polyphase watthour meter are a combination of single-phase watthour meter elements. The main meter parts consist of multi-electromagnetic elements, a magnetic braking system, the moving elements, a register and any necessary compensating devices.

The basic operation of a single-phase induction watthour meter is as follows: A torque is created in an induction watthour meter which causes a rotor disk to turn which in turn drives a number of counting dials at a speed proportional to the product of the supply voltage (E_S) and the load current (I_S). This torque is a result of eddy currents in the disk producing a magnetic flux opposing the inducing flux [the

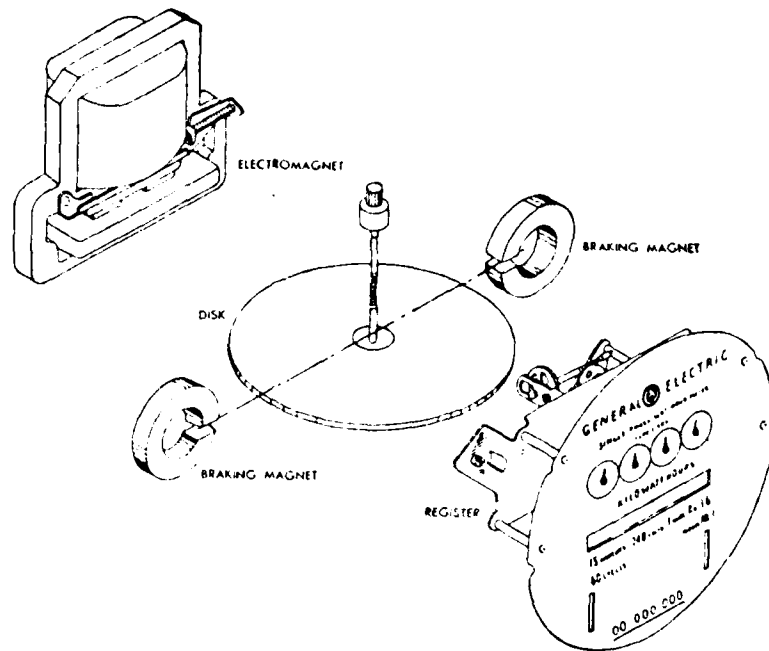


Figure 4.11 Principle Parts of a Single-Phase Induction Watthour Meter

Source: General Electric, Manual of Watthour Meters, GET-1840 (New York: General Electric, 1950) p. 13.

inducing flux is caused by a combined action of a magnetic flux proportional to the supply voltage and a magnetic flux proportional to the load current]. The net torque on the disk then becomes proportional to

$$T \propto E_S I_S \cos \theta \quad (4.8)$$

where $\cos \theta$ is the load power factor. It should be noted that although frequency is absent from equation 4.8, it will affect the induced eddy currents and hence the torque. Thus, an induction watt-hour meter is normally only suitable for use at its calibrated frequency. As a

result, nonsinusoidal signals with high harmonic content can cause serious errors (-10 to +30% error [28] [29]) in induction watt-hour meter readings. A more detailed explanation of the induction watt-hour meter operation follows.

Theory of Operation

A single-phase induction watt-hour meter uses induction motor action to create its driving torque [23,24,25,27,30,31]. Figure 4.12 shows the fluxes produced for a single-phase watt-hour meter operating at unity power factor.

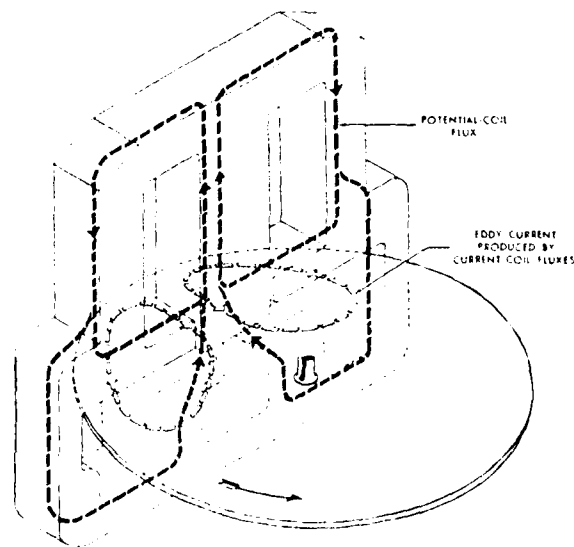


Figure 4.12 Generation of Driving Torque in a Single-Phase Watt-hour Meter at Unity Power Factor

Source: General Electric, Manual of Watt-hour Meters, GET-1840 (New York: General Electric, 1950) p. 16.

The rotor of the motor is an aluminum disk mounted concentrically on a shaft. The stator of the motor is an electromagnet which has two sets of windings assembled on a laminated, soft-iron core. One winding, called the potential coil, is connected across the load; the other

winding, called the current coil is connected in series with the load. The internal wiring diagram of a single-phase watthour meter is shown in figure 4.13.

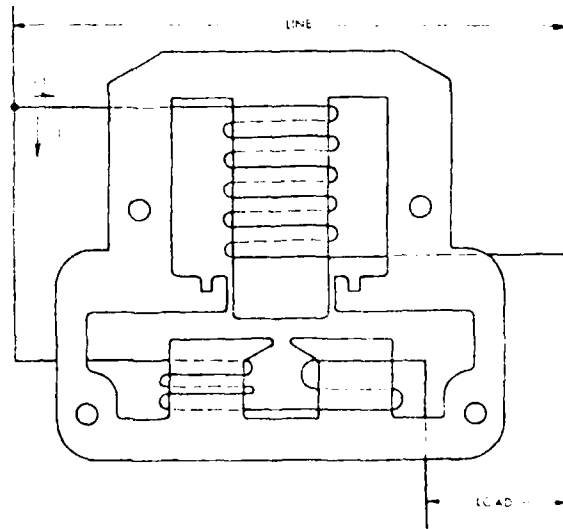


Figure 4.13 Internal Wiring Diagram of Single-Phase Induction Watthour Meter.

Source: General Electric, Manual of Watthour Meters, GET-1840 (New York: General Electric, 1965) p. 15

The mathematical analysis of an induction watthour meter is as follows: Assume that the current coil carries a current I_1 and produces a flux Φ_1 that is proportional and in phase with I_1 . Also assume that the potential coil, which has a high inductance and negligible resistance, has a current I_2 which is equal to $V/\omega L$. The flux Φ_2 caused by I_2 is proportional to $V/\omega L$ and lags V by 90° . If the load current has a lagging phase angle ϕ , then Φ_1 lags V by angle ϕ and Φ_2 lags Φ_1 by $(90-\phi)$. The phasor diagram for this configuration is shown in figure 4.14.

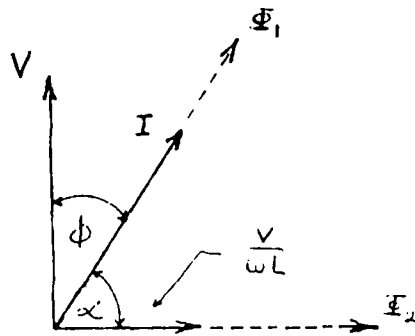


Figure 4.14 Phasor Diagram for Single-Phase Induction Watthour Meter

Source: C.T. Baldwin, Fundamentals of Electric Measurements (New York: Frederick Ungar Publishing Co., 1961) p. 125.

Thus the equations for both an induction watthour meter as well as an induction wattmeter are

$$T = K\omega \phi_1 \phi_2 \sin \alpha \quad (4.9)$$

and

$$T \propto \omega I \frac{V}{\omega L} \sin (90-\phi) \quad (4.10)$$

or

$$T \propto VI \cos \phi \quad (4.11)$$

A further analysis of the induction watthour meter structure shows that it is somewhat like a transformer that has two primary windings and two secondaries. The primary windings are the potential and current coils. The secondaries consist of separate eddy-current paths within the disk. Because the disk cuts the flux produced by the current in each of the two coils, potentials are induced in the part of the disk that is in the air gap. Since the disk provides closed circuits, the induced voltages cause alternating currents (eddy

currents) to flow. These currents react with the potential coil and current coil fluxes to produce torque.

Since the driving torque developed by equation 4.11 is always proportional to the load current, the line voltage, and the power factor; the torque, as well as being a measure of the energy used, can be made to be a measure of the average power. A watthour meter mechanism can be used as a wattmeter mechanism by adding a pointer, scale and counter-torque spring. It should also be noted that an induction watthour meter operates only on alternating current circuits, since their operation depends on the production of alternating currents by alternating fluxes. As a result, the induction watthour meter is not useful for measuring dc energy or power and would measure in error in an ac circuit that has a high d.c. current component. This statement will be verified in Part II of this thesis.

Conclusion

Because the induction watthour meter is not independent of wavetform or frequency variations and because the induction watthour meter is not designed to measure dc power, the use of this meter for measuring non-sinusoidal power, especially when a large dc component is present is questionable. Although past research has shown an error of less than ± 10 per cent occurs when standard industrial watthour meters are subjected to nonsinusoidal power variations, the verdict is not out as to whether this error is too excessive under the worst conditions or whether this error will increase under future loading conditions.

CHAPTER 5

MEASUREMENT STANDARDS, TYPES OF MEASUREMENT ERRORS, LIMITING OR GUARANTEE ERRORS, PRECISION AND ACCURACY

This chapter defines the different types of measurement standards and the various types of measurement errors which occur in making measurements. It discusses the effects of limiting or guarantee errors and how they relate to the actual percent error when comparing readings at different points on a meter scale. This chapter defines the terms precision and accuracy and concludes by showing how all of the above are applied to power measurements.

5.1 Measurement Standards

There are four different types of standards of measurement which are classified [25,30,32] by their function and application into the following categories:

- (a) International Standards
- (b) Primary Standards
- (c) Secondary Standards
- (d) Working Standards

The International Standards are defined by international agreements and are maintained at the International Bureau of Weights and Measures and are not available to the ordinary user of measuring instruments for purposes of comparison or calibration. The Primary Standards are maintained by national standards laboratories in different parts of the world. The National Bureau of Standards (NBS) in Washington is responsible for maintenance of the primary standards in North

America. The primary standards are not available for use outside the national laboratories but are used primarily for the verification and calibration of secondary standards. The Secondary Standards are the basic reference standards used in industrial or college high precision measurement laboratories. They are periodically sent to the NBS laboratory for certification of their measured value in terms of the primary standard. The fourth type of measurement standards are the Working Standards which are used in measurement laboratories requiring precision measurements. Both the secondary standards and the working standards are at times classified as "Transfer Standards." The General Electric Type P-3 Electrodynamometer wattmeter is classified as a transfer standard and is used as the reference standard in Part II of this thesis.

5.2 Types of Measurement Errors

The error in a measurement is defined as the algebraic difference between the indicated or measured value and the true value. It is stated in reference [30] that the true value can never be found (that is the measured value must always be expressed with a tolerance or uncertainty factor) and as a result the "true value" is replaced by "the conventional true value" which is the value the measurand can be realistically accepted as having. In order to get the most accurate measurement possible it is necessary to define the different types of errors and their causes. Errors are usually classified [25,30,32] under three main headings:

- (a) Gross Errors,
- (b) Systematic Errors,
- (c) Random Errors.

Gross errors mainly result from "human" mistakes in reading or using instruments and in recording and computing measurement results. Systematic Errors are further classified as Instrumental errors, Environmental errors, and Observational errors. Instrumental errors are errors inherent in the measuring instrument because of its physical or mechanical construction. Irregular spring tension and improper scale divisions are examples of instrumental errors. Insertion error or meter loading can be classified as a gross or instrumental error. The effects of instrument component ageing is also an example of an instrumental error. Environmental errors are errors due to conditions external to the measuring device, including conditions in the area surrounding the instrument. Changes in temperature, humidity, barometric pressure, magnetic or electrostatic fields may result in improper operation of the instrument and the resulting error would be an environmental error. Observational errors are errors that result from the observer's use of the instruments. As a result, several observers using the same equipment for duplicate sets of measurements do not necessarily produce duplicate results due to the fact that some observers will read the meter consistently high while other observers will read the meter consistently low. Systematic errors are also at times divided into static or dynamic errors. Static errors are errors caused by limitations of the measuring device or the physical laws governing its behavior. Dynamic errors are errors caused by the instrument not responding fast enough to follow the changes in a measured variable. Systematic errors are those which consistently reoccur when a number of measurements are taken. They may be caused by deterioration of the measurement system (weakened magnetic field,

change in reference resistance value), alteration of the measured value by the addition or extraction of energy from the element being measured, response-time effects, and attenuation or distortion of the measurement signal.

The last major type of errors are Random errors. Random errors are due to unknown causes and occur even when all systematic errors have been accounted for. Random errors are often a result of neglecting second order or residue effects. Random errors may also be a result of noise or induced signals occurring during transient or steady state conditions. Random errors are accidental, tend to follow the laws of chance, and do not exhibit a consistent magnitude or sign.

5.3 Limiting or Guarantee Errors

In most indicating instruments, the accuracy is guaranteed to a certain percentage of full-scale reading. Circuit components are guaranteed within a certain percentage of their rated value. The limit of these deviations from the specified values are known as limiting errors or guarantee errors [25]. The effect of limiting error is shown by the following example:

Example 5.1

A 0-500w wattmeter has a guaranteed accuracy of 1 per cent of full-scale reading. The power measured is a) 450w and b) 50w respectively. Calculate the limiting error in per cent.

The magnitude of limiting error is

$$0.01 \times 500w = 5.0w$$

the percentage error is

$$a) \frac{5}{50} \times 100\% = 10.0\%$$

$$b) \frac{5}{450} \times 100\% = 1.1\%$$

The above example shows clearly how a meter can be specified as having an accuracy of 1% of full scale but actually have a limiting error of greater than 10% at the low end of the scale. This is why a meter should be read as close to full scale as possible. The above limiting error is not only applicable to analog meters but to digital meters as well.

The factors which make up the accuracy or limiting error of a measuring instrument can be partially accounted for by looking at the effect that different types of errors have on pointer position. This is shown graphically in figure 5.1.

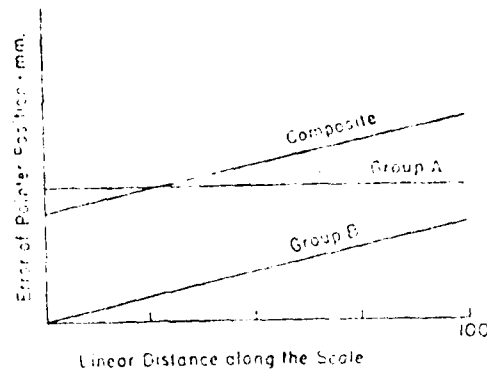


Figure 5.1 Curves Showing Variation Along the Scale of Various Types of Instrument Error

Source: Melville B. Stout, Basic Electrical Measurements, (New Jersey: Prentice-Hall, 1960) p. 476.

Figure 5.1 shows that some errors (Group A) affect the instrument indication about equally at all parts of the scale, while others (Group B) increase in proportion to the reading. The abscissa represents the scale of the instrument. Errors, plotted as ordinates to a

linear scale, represent the actual distance the instrument pointer is from its true position. The errors are classified [33] into two groups.

(a) Group A

This group comprises those effects that tend to produce errors of the same magnitude at any point of the scale and include scale error, zero error, reading error, parallax error and friction error.

(b) Group B

This group comprises those effects that produce errors proportional to the pointer deflection and include errors caused by incorrect resistance, the effects of temperature on resistance, control springs, and the strength of permanent magnets in dc instruments, the effect of frequency on reactive components.

The total error experienced is made up of the effects from Group A and B but the actual error may differ as the components enter to different extent in various cases. The Composite curve of figure 5.1 illustrates the general effect that may be expected. It should be noted that smaller errors may be anticipated at midscale than at full scale but not in proportion to the readings.

The net result of limiting error is that the error at different parts of the scale is more nearly constant in actual amount than it is as a percentage of the reading being taken. Therefore, the abbreviated marking "Accuracy: 1.0 per cent" really means that the error at any point on the scale will not exceed 1.0 per cent of the full-scale reading.

5.4 Precision and Accuracy

Precision and accuracy are often thought of as being interchangeable. In measurement work, however, it is necessary to provide

further distinction between the two. Precision and accuracy are defined as follows:

(a) Precision

- (1) Precision refers to the degree of agreement within a group of measurements or instruments. It is composed of two characteristics: conformity and the number of significant figures to which a measurement may be made [25].
- (2) Precision is a measure of the reproducibility of the measurement or is a measure of the degree to which successive measurements differ from one another [25].
- (3) Precision is a measure of the spread of repeated determinations of a particular quantity. Precision depends on the resolution (the smallest change in measured value to which the instrument will respond) of the measurement means and variations in the measured value caused by instabilities in the measurement system [33].

(b) Accuracy

- (1) Accuracy refers to the degree of closeness or conformity to which an instrument reading approaches the true value of the variable being measured [25].
- (2) Accuracy is conforming exactly to truth or to a standard [32].
- (3) Accuracy is a statement of the limits which bound the departure of a measured value from the true value. Accuracy includes the imprecision of the measurement along with all the accumulated errors in the measurement

chain extending from the basic reference standards to the measurement in question [33].

- (4) Accuracy is the quality which characterizes the ability of a measuring instrument to give indications equivalent to the true value of the quantity measured. It should be expressed in terms of tolerance or uncertainty [30].

It can be deduced from the above definitions that a measurement system may provide precise readings, all of which are inaccurate because of an error in calibration or a defect in the system. It can also be said that precision is a necessary prerequisite for accuracy but precision does not guarantee accuracy.

5.5 Conclusions

The application of measurement standards, a knowledge of different types of errors, and a clear understanding of the distinction between precision and accuracy are all necessary ingredients for accurately measuring power. The need for defining the variables that can affect measurements is often overlooked and as a result, the experimental data produced and conclusions drawn are in error. Another reason for considering the above variables prior to doing any experimental work is that it gives the experimenter a chance to devise sound experimental techniques that eliminate many of the gross and systematic errors. The next three chapters summarize the gross, systematic and random errors that are associated with the test equipment used in Part II of this thesis.

CHAPTER 6

FACTORS WHICH AFFECT THE ACCURACY OF THE CLARKE-HESS, MODEL 255 V-A-W METER

This chapter discusses the types of gross, systematic and random errors that may occur with the use of the Clarke-Hess, Model 255 Digital Wattmeter [20,30,34]. It discusses the limiting or guarantee error which in essence defines the accuracy of the Model 255 wattmeter. The chapter concludes with a discussion of why the Clarke-Hess, Model 255 V-A-W meter is an accurate power measuring device.

6.1 Gross Errors

The gross errors associated with the operation of the Model 255 wattmeter result from failure to zero meter, failure to read the digital display properly, failure to apply any necessary correction factors, failure to notice an "input overload" condition and failure to record the data correctly. For the Model 255 wattmeter the gross errors are normally negligible and can be kept to a minimum if multiple readings are taken and if good experimental techniques are used.

6.2 Systematic Errors

The systematic errors associated with the operation of the Model 255 wattmeter are classified as a) instrumental errors and b) environmental errors.

a) Instrumental Errors

Instrumental errors are inherent meter errors caused by:

- (1) instrument power losses
- (2) changes in power factor
- (3) changes in frequency
- (4) crest factor
- (5) measurement rate
- (6) changes in waveform
- (7) ageing electrical properties

The following is a discussion of the instrumental errors that may be associated with the operation of the model 255 wattmeter.

(1) Instrument Power Loss

The instrument power losses associated with the Model 255 are a result of insertion losses due to the physical connections made by the voltage and current circuits. The two methods for connecting the Model 255 wattmeter for measuring power are shown in figure 6.1(a) and 6.1(b).

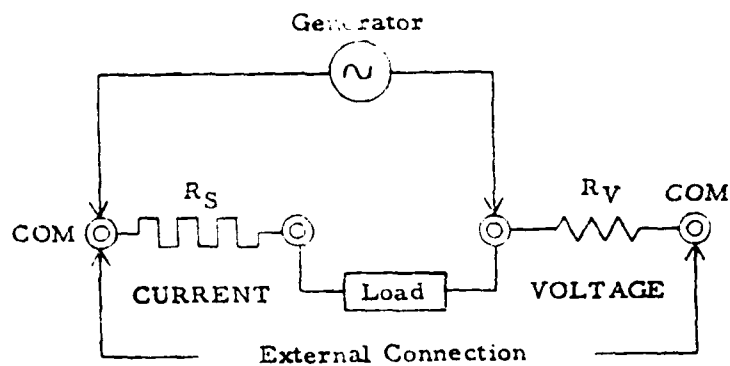


Figure 6.1(a) I^2R_S Correction Connection

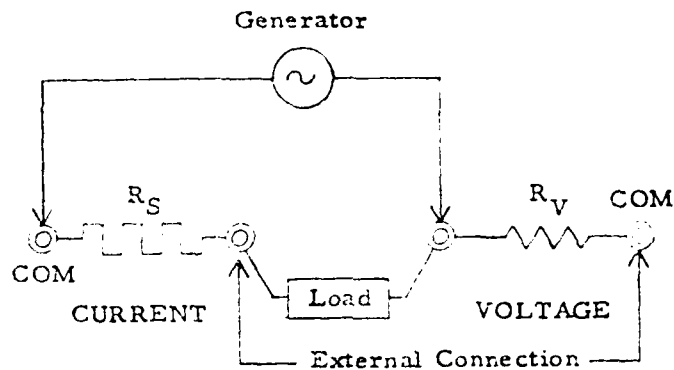


Figure 6.2(b) V^2/R_V Correction Connection

Source: Clarke-Hess, Operation Manual for Clarke-Hess Model 255 V-A-W Meter (New York: Clarke-Hess, 1980) p. 1-4

In figure 6.1(a) the wattmeter reads high by the correction factor (I^2R_S) since the current I passes through the current-circuit resistance (R_S). As a result this added power loss needs to be subtracted from the reading. In figure 6.1(b) the wattmeter reads high by the correction factor (V^2/R_V) since the voltage drop across the voltage circuit resistance (R_V) results in an added power loss which must be subtracted from the reading. The type of connection to be used is dependent on which connection will give a more accurate reading. Normally for the Model 255 wattmeter the I^2R_S connection is used because of the capability of the meter to expand power measurements on a PX10 position. In this position both the input voltage and input current must be less than 40 per cent of their full scale values. The result of using the PX10 position is an additional decade of resolution which results in a more precise reading. In the

PX10 position the I^2R_S connection should be used. For the Model 255 wattmeter with a 120 volt supply and a circuit current between 0 to 5 amps, the V^2/R_V loss is approximately 0.003 watts and the I^2R_S loss varies between 0 to 0.7 watts. I have used the I^2R_S connection in my experimental work to allow for use of the expanded PX10 position as well as for circuit wiring consistency with the VM-63-S induction watt-hour meter and the P-3 analog wattmeters.

(2) Changes in Power Factor

The Model 255 is affected by changes in power factor. See table 6.1 for variations in stated accuracy as both the power factor and frequency is changed. The type of connection used (either I^2R_S or V^2/R_V) for measuring power has little affect near unity power factor. At very low power factors the I^2R_S connection should not be used because serious errors between 75 to 90 per cent could result due to insertion losses. The accuracy data above assumes that proper correction term and connection has been applied. In the experimental work done in Part II of this thesis, changes in power factor did not have a significant effect as the power factor was maintained greater than 0.5.

(3) Changes in Frequency

The accuracy of the Model 255 is affected by changes in frequency as can be seen by Table 6.1. One of the main causes for this accuracy change is due to changes in the series impedance of the current circuit. At low frequencies this impedance is resistive. At high frequencies the input series

Table 6.1
Specifications for Accuracy

POWER

$$\text{Power Factor}^{(1)} = \frac{\text{Power}}{\text{Input V A}} \geq 0.5$$

Input V A Range/Range	30Hz (1)	50Hz/60kHz	60kHz/100kHz
less than 15	±0.6% F.S. ±0.4% V A	0.4% F.S. 0.2% V A	0.6% F.S. 0.6% V A
between 15 and 25	+1% V A	0.6% V A	1% V A

$$\text{Power Factor}^{(2)} = \frac{\text{Power}}{\text{Input V A}} \geq 0.5$$

Input V A Range/Range	30Hz/25kHz	25kHz/50kHz	50kHz/100kHz
less than 15	±0.4% F.S. ±0.2% V A	0.5% F.S. 0.5% V A	0.7% F.S. 0.8% V A
between 15 and 25	+0.6% V A	1% V A	1.5% V A

Notes: (1) The accuracy is dependent on the power factor of the load. Accuracy is given for a power factor of 0.5.

(2) The accuracy is dependent on the power factor of the load. Accuracy is given for a power factor of 0.5. The accuracy is also dependent on the frequency of the load. Accuracy is given for a frequency of 60 Hz. The accuracy is also dependent on the range of the load. Accuracy is given for a range of 15 to 25 V A.

Adapted from Clarke-Hess, Operation
Manual for the Clarke-Hess Model 255
V-A-W Meter(New York: Clarke-Hess, 1980)
Specifications

impedance may contain a significant inductive component. The effect of frequency change on the experimental data in Part II was negligible due to low operating frequency (60 Hz).

(4) Crest Factor

Crest factor [34] is the ratio of the peak value to the rms value of an ac waveform. The Model 255 will normally measure pulse or spike inputs with peak values of four times the full scale dc value. In the case of peak to peak values around a zero average the Model 255 will measure spike inputs

up to eight times the full scale dc value. The ability of the Model 255 sensing circuitry to operate and respond to these dynamic changes in amplitude adds to the accuracy of the power measurement. For most input signals including diode rectified and SCR waveforms the crest factor is normally less than 3:1. The Model 255 is rated at crest factors up to 3:1 and as a result crest factor had a negligible effect on the experimental data in Part II.

(5) Measurement Rate

The measurement rate and the display rate are locked to the power line frequency and are normally set at 10 readings per second for 60 Hz operation. This sampling rate was fast enough for the data taken in Part II.

(6) Changes in Waveforms

Waveform variations can have an effect on the Model 255's measuring circuitry if the sampling rate is not fast enough to measure the input signal variations or if the crest factor limitations are exceeded. Since the Model 255 is a true rms and instantaneous measuring device and since neither the sampling rate or crest factor limitations were exceeded, waveform errors were considered negligible for the testing done in Part II.

(7) Ageing Electrical Properties

The effect of ageing on various circuit components is not specified in the operations manual. The tolerance or accuracy of the Model 255 is guaranteed for one year. If practical and cost effective, the Model 255 should be recalibrated every

year. For the Model 255's used in Part II the calibration dates were December 1980 for SN 656 and SN 657 and June 1982 for SN 5955. These meters were bought and shipped to Colorado State University around January and August 1982 and were tested in Part II without recalibration due to economic considerations as well as the fact that these meters were hardly ever used and hopefully had maintained their accuracy. Operational calibration procedures were performed prior to testing.

b) Environmental Errors

The environmental errors are errors due to external and internal influences not associated directly with the components that go into the fabrication of the instrument. Some of the environmental errors that may arise for the Model 255 are caused by:

- (1) ambient-temperature influence
- (2) self heating influence
- (3) stray-field influence

The following is a discussion of environmental errors that may be associated with the operation of the Model 255 wattmeter.

(1) Ambient-temperature Influence

Normally, digital meters have a specific per cent change per degree centigrade change (eg. + 0.01 per cent per degree centigrade). The specifications for the Model 255 state an operating temperature range of 0°C to 50°C with specified accuracy maintained between 15°C to 35°C. For the

experimental work done in Part II all tests were conducted within the specified temperature range.

(2) Self-heating Influence

The self-heating influence is caused by the temperature rise due to the I^2R losses in the instrument. For the model 255 the 5 amp scale will have a "drift" caused by self-heating of the internal shunt if it is used for currents above 7.5 amperes. For the experimental work in Part II, the current was maintained below 5 amperes so this effect was negligible.

(3) Stray-field Influence

The influence of stray fields on the model 255 is not specified. Since specific manufacturing design criteria is not specified and since no external fields were introduced for the experimental work, the effect of stray-field influence is considered negligible for the experimental work done in Part II.

6.3 Random Errors

The random errors associated with the operation of the Model 255 wattmeter are unpredictable and probably would be a result of noise or transient over- or under-voltage conditions. Random errors are considered to be negligible unless specifically stated as an experimental variable in Part II of this thesis.

6.4 Limiting or Guarantee Error

As mentioned in Chapter 5, the Model 255 is subject to limiting or guarantee error. The limiting error or stated accuracy for the Model

255 is ± 0.6 per cent of full scale and ± 0.4 per cent of the reading for dc to 30 Hz and ± 0.4 per cent of full scale and ± 0.2 per cent of the reading for 30 to 50 KHz at power factors greater than 0.5. The following example illustrates this error. For a reading of 500 watts on a 60 Hz system and using the 5 amp and 1000 volt range, a limiting error of $(20 + 1) \pm 21$ watts could occur. For a reading of 500 watts using the 5 amp and 200 volt range, a limiting error of $(4 + 1) \pm 5$ watts could occur. This limiting error could be very significant at low power readings.

6.5 Conclusions

The Clarke-Hess Model 255 Wattmeter is a versatile and accurate measuring device and can be used to measure dc, sinusoidal and non-sinusoidal power. The effects of gross or human errors are kept to a minimum if good experimental technique is used. The effects of systematic errors due to changes in power factor, frequency and waveform are negligible. The Model 255 is a fast responding measuring device and will measure signals with a crest factor of up to 3 to 1 accurately. The two most important systematic errors occur due to instrument insertion power losses and due to the ageing properties of electrical components. Both of these instrumental errors can be minimized if power loss correction factors and proper meter connections are used and if the meter is calibrated on a yearly basis. The effects of environmental errors due to (1) ambient-temperature influence (2) self-heating influence and (3) stray-field influence are negligible if the Model 255 is operated in its normal temperature and current range and environment. The effects of random errors on the Model 255 are unpredictable and are considered to be negligible. The

effect of limiting or guarantee error is only significant at low power readings at the low end of the voltage X current power range.

The reason why the Clarke-Hess Model 255 is an accurate measuring device results from its ability to measure instantaneously the average power through the use of its digital electronic circuitry. The Model 255 is not adversely affected by many of the normal types of meter errors and offers low circuit loading. The accuracy of the Model 255 is sufficient for most college and industrial applications and its versatility as an rms voltage and current and average power meter makes it a very useful meter for measuring all types of circuit parameters.

CHAPTER 7

FACTORS WHICH AFFECT THE ACCURACY OF THE GENERAL ELECTRIC TYPE P-3 ELECTRODYNAMIC WATTMETER

This chapter discusses the types of gross, systematic and random errors that may occur with the use of the General Electric Type P-3 Electrodynamic wattmeter [23,22,23,24,30,32]. It discusses the limiting or guarantee error which in essence defines the accuracy of the P-3 wattmeter. The chapter concludes with a discussion of why the General Electric Type P-3 Wattmeter is an accurate power measuring device.

7.1 Gross Errors

The gross errors associated with the operation of the P-3 wattmeter result from failure to zero the meter, failure to read the meter properly and apply any necessary correction or multiplying factors, parallax error, and errors in recording the data correctly. For the P-3 wattmeter the gross errors are normally negligible and can be kept to a minimum if multiple readings are taken and if good experimental techniques are used.

7.2 Systematic Errors

The systematic errors associated with the operation of the P-3 wattmeter are classified as: a) instrumental errors and b) environmental errors.

a) Instrumental Errors

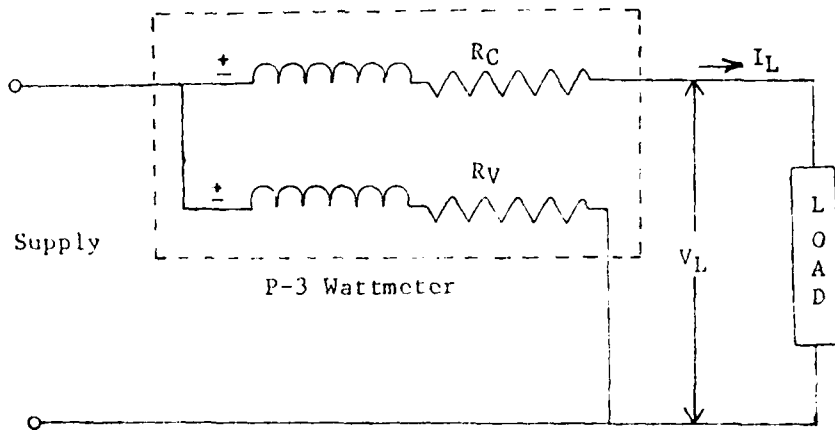
Instrumental errors are inherent meter errors caused by:

- (1) instrument power losses
- (2) voltage-coil inductance
- (3) voltage-coil capacitance
- (4) mutual inductance
- (5) eddy currents
- (6) changes in power factor
- (7) changes in frequency
- (8) changes in waveform
- (9) physical construction defects
- (10) ageing electrical and mechanical properties

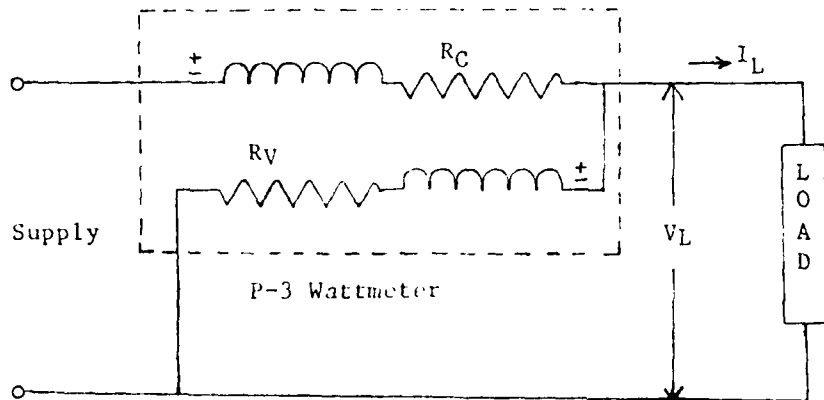
The following is a discussion of instrumental errors that may be associated with the operation of the P-3 wattmeter.

(1) Instrument Power Loss

The instrument power losses associated with the P-3 wattmeter are a result of insertion losses due to the physical connections made by the voltage and current-coil circuits. The two methods for connecting the P-3 wattmeter for measuring power are shown in figure 7.1(a) and 7.1(b). In figure 7.1(a) the wattmeter reads high by the correction factor $(I_L^2 R_C)$ since the current I_L passes through the current coil resistance (R_C). As a result this added power loss needs to be subtracted from the reading. In figure 7.1(b) the wattmeter reads high by the correction factor (V_L^2/R_V) since the voltage drop across the voltage coil resistance (R_V) (neglecting any inductive effects of the



7.1(a) $I_L^2 R_C$ Correction Connection



7.1(b) V_L^2 / R_V Correction Connection

voltage coil) results in an added power loss which must be subtracted from the reading. The type of connection to be used is dependent on which connection will give a more accurate reading. Normally for the P-3 wattmeter the $I_L^2 R_C$ connection is more accurate below an rms current of 4.0 amps. In practice however, the V_L^2 / R_V connection is normally used because it is easier to correct for a relatively constant loss in the voltage-coil circuit than

for the varying loss in the current-coil circuit. For the P-3 wattmeter the $I_L^2 R_C$ losses vary between 0 to 2.0 watts, while the V_L^2 / R_V losses are constant at 1.3 watts. I have used the $I_L^2 R_C$ connection in my experimental work for circuit wiring consistency with the VM-63-S induction watt-hour meter and the Clarke-Hess digital wattmeters.

(2) Voltage-coil Inductance

The torque developed in the P-3 wattmeter is a result of the load current I_L and the voltage-coil current I_V and the angle between these currents, where

$$T \propto I_L I_V \cos \theta \quad (7.1)$$

If the effect of inductance in the voltage coil is neglected, then torque is related as follows

$$T \propto \frac{IV}{R} \cos \theta \quad (7.2)$$

where I is the current-coil current, V is the voltage coil voltage and R is the voltage coil resistance. In practice, the voltage coil has some inductance (P-3 voltage coil inductance is approximately 5 milli-henrys) and a resulting reactance. This reactance results in phase displacement (α) for current I_V . See figure 7.2 (a) and (b) for phasor diagrams with and without inductive effects.

The resulting effect of inductance is that the voltage-coil current I_V is altered and equal to

$$I_V = \frac{V}{R} \cos \alpha \quad (7.3)$$

where

$$\cos \alpha = \frac{R}{\sqrt{R^2 + X^2}} \quad (7.4)$$

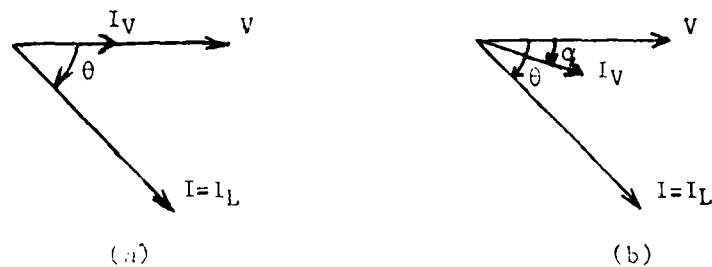


Figure 7.2 (a) Non-inductive Voltage Coil
(b) Inductive Voltage Coil

Source: C.T. Baldwin, Fundamentals of Electric Measurements, (New York: Frederick Ungar Publishing Co., 1961), p. 91

and the resulting torque becomes

$$T \propto \frac{IV}{R} \cos \alpha \cos (\theta - \alpha) \quad (7.5)$$

Comparison of equation (9.2) and (9.5) shows that the correction factor by which the torque or deflection must be

multiplied is

$$\frac{\cos \theta}{\cos \alpha \cos (\theta - \alpha)} \quad (7.6)$$

For the P-3 wattmeter α is normally very small and has little effect for low frequency, sinusoidal input signals.

(3) Voltage-coil Capacitance

Capacitance is present in the series resistance of the voltage-coil circuit. The net effect of this capacitance is to reduce the angle or offset the inductance of the voltage coil. Normally at power-line frequencies and at power factors above 0.5 the effect of capacitance is negligible for the P-3 wattmeter.

(4) Mutual Inductance

A small error may be introduced in the P-3 wattmeter due to mutual inductance between the current and voltage coils. A small emf is induced in the voltage-coil circuit due to the load current in the current coil. This error is normally very small for the P-3 wattmeter and is not easily calculated unless the variation in mutual inductance with angle θ is known. The net effect of mutual inductance would cause the meter to read low with lagging power factor loads and high with leading power factor loads at the upper half of the scale and read high with lagging power factor loads and low with leading power factor loads at the lower half of the scale.

(5) Eddy Currents

Any mass of metal in close proximity to a coil carrying current will have eddy currents induced in it and the magnetic field produced by these currents will react with the current and voltage coil fields. The net effect will have some negligible effect on deflecting torque and will vary with power factor. For the P-3 wattmeter this effect is negligible as the metal structure is kept to a minimum and is chosen of material with low hysteresis, high saturation density and high resistivity.

(6) Changes in Power Factor

Power factor errors are caused by the inductive reactance of the voltage and current coils which cause the current to lag the voltage dependent on the frequency of the circuit. As stated under the voltage-coil inductance explanation the phase angle between the load current and voltage coil current is adversely affected. The net effect, especially at low power factor and high frequency, is a reduction in torque. This reduction in torque can result in error if the control spring is not designed to offer less countertorque. In the case of the P-3 wattmeter, it is not designed to be a low power factor meter and should be operated above 0.5 power factor.

(7) Changes in Frequency

Frequency errors are errors caused by the effect of too high or too low of a frequency. As mentioned earlier, higher frequencies cause more inductive reactance and

result in less current at a greater phase displacement in the voltage-coil circuit. This effect is more pronounced in iron-core than in air-core instruments and is one reason why the voltage coil of the P-3 wattmeter is made with a minimum number of turns necessary to provide adequate torque. Frequency errors are also related to eddy current losses as the eddy current losses increase at higher frequency. Generally speaking, the P-3 wattmeter is negligibly affected by frequency errors primarily due to its low inductance.

(8) Changes in Waveform

Waveform errors are errors caused by the meter being adversely affected by non-sinusoidal or non-periodic signals. These signals or distorted waves are composed of several harmonics above the fundamental and the net result is similar to frequency distortion where the inductive reactance of the current and voltage coil changes. This change in inductive reactance can cause a change in voltage and current-coil current and result in a greater phase displacement which affects the torque developed and hence the power reading. The effect of waveform errors on the P-3 is considered to be negligible.

(9) Physical Construction Defects

Physical construction defects are normally a result of errors introduced in the manufacture of the meter. Some possible construction defects which would result in error could be scale errors, frictional errors due to the pivot

or jewel being too loose or too tight and errors due to improper spring tension. For a calibrated P-3 wattmeter it is assumed that these errors are negligible.

(10) Ageing Electrical and Mechanical Properties

The effects of ageing in the electrical properties such as resistance and inductance over time is negligible for the P-3 wattmeter. The effects of ageing in the mechanical properties such as spring tension and pivot and jewel wear may be significant if not calibrated on a regular basis. The construction of the P-3 wattmeter is of high precision quality parts and normally errors due to ageing are negligible.

b) Environmental Errors

Environmental errors are errors due to external and internal influences not associated directly with the components that go into the fabrication of the instrument. Some of the environmental errors that may arise are caused by:

- (1) ambient-temperature influence
- (2) self-heating influence
- (3) stray-field influence

The following is a discussion of environmental errors that may be associated with the operation of the P-3 wattmeter.

(1) Ambient-temperature Influence

Changes in ambient temperature affect the resistance of the instrument and the elasticity of its control spring. The resistance of the voltage coil has a positive temperature coefficient which could cause the meter to read low

as the ambient temperature rises. The effect of resistance change is offset by the effect of the control spring change. The control spring has a negative temperature coefficient which could cause the meter to read high as the ambient temperature is raised. The overall effect of ambient-temperature on the P-3 wattmeter appears to be negligible. The specification on the P-3 meter states that the change in reading does not exceed 0.01 per cent per degree centigrade.

(2) Self-heating Influence

The self-heating influence is caused by the temperature rise due to the I^2R losses in the instrument windings and resistance. The overall effect of self-heating on the P-3 wattmeter appears to be negligible as compensation is provided. The specification on the P-3 meter states that the change in reading does not exceed 0.2 per cent of full scale reading.

(3) Stray-field Influence

The influence of stray fields on the electrodynamic meter movement is serious due to the small operating fluxes. In the design of the P-3 wattmeter the effect of stray fields is negligible because of the use of a laminated-iron shield and because of the physical construction of the current and voltage coils cancels the torque created by these stray fields.

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MEASURING ACCURATELY SINGLE-PHASE SINUSOIDAL AND
NON-SINUSOIDAL POWER(U) AIR FORCE INST OF TECH
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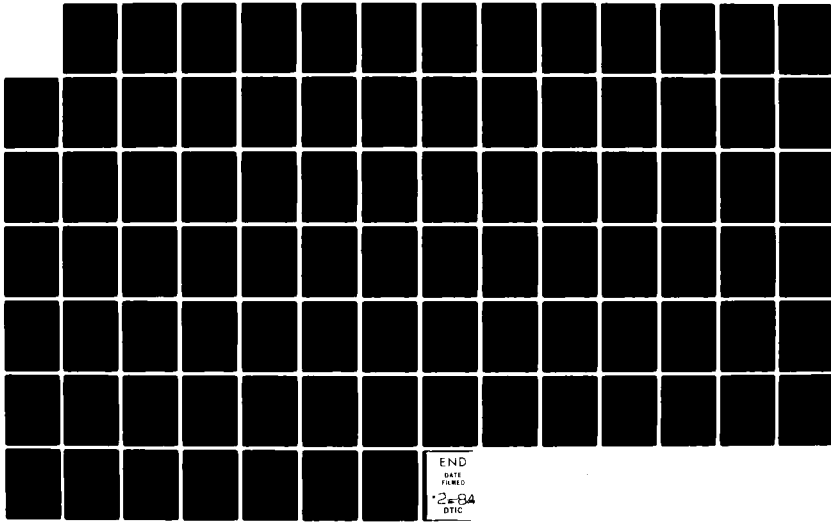
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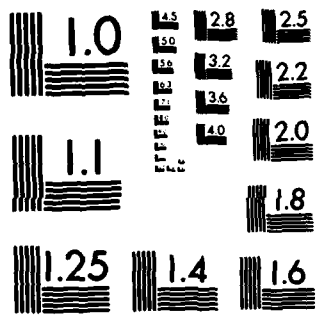
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7.3 Random Errors

The random errors associated with the operation of the P-3 wattmeter are unpredictable and probably would be a result of noise or transient over or under-voltage conditions. Random errors are considered to be negligible unless specifically stated as an experimental variable in Part II of this thesis.

7.4 Limiting or Guarantee Error

As mentioned in Chapter 5, the P-3 wattmeter is subject to limiting or guarantee error. The limiting error or stated accuracy for the P-3 wattmeter is specified as ± 0.2 per cent of full scale value or direct current and on alternating current of any frequency up to 133 Hz at power factors greater than 0.5. The limiting error for the P-3 wattmeter translates to a ± 1 watt to ± 4 watt error depending on scale being used. This error is normally only significant at readings at the low end of the scale.

7.5 Conclusions

The General Electric Type P-3 Electrodynamometer wattmeter is a versatile and accurate measuring device and can be used to measure dc, sinusoidal and non-sinusoidal power. The effects of gross or human errors are kept to a minimum if good experimental technique is used. The effects of systematic errors due to voltage-coil inductance and capacitance, mutual inductance, eddy currents, changes in frequency and changes in waveform are negligible. Systematic errors due to changes in power factor are negligible if power factor is greater than 0.5. The systematic errors that occur most often are errors due to insertion losses, physical construction defects and the ageing of

mechanical components such as bearings and springs. All of these systematic errors can be minimized if power loss correction factors are used and if regular calibration and maintenance is performed. The effects of environmental errors due to (1) ambient-temperature influence, (2) self-heating influence, and (3) stray-field influence are negligible if operated in its normal temperature and current range and environment. The effects of random errors are unpredictable and are considered negligible. The effect of limiting or guarantee error is only significant at low power readings (below 50 watts).

The reason why the P-3 electrodynamic wattmeter is an accurate measuring device results from its ability to measure instantaneously the average power by developing a torque which is proportional to the instantaneous voltage and current. This accuracy is also a result of high precision and high quality parts used in its fabrication. The P-3 wattmeter is not adversely affected by many of the normal types of meter errors and offers low circuit loading at low frequencies.

CHAPTER 8

FACTORS WHICH AFFECT THE ACCURACY OF THE GENERAL ELECTRIC, TYPE VM-63-S INDUCTION WATTHOUR METER

This chapter discusses the types of gross, systematic, and random errors that may occur with the use of the General Electric Type VM-63-S Class 10 Induction Watthour Meter [23,27,31,35]. It discusses the limiting or guarantee error which in essence defines the accuracy of the induction watthour meter. The chapter concludes with a discussion of why the VM-63-S induction watthour meter is or is not an accurate energy (power) measuring device.

8.1 Gross Errors

The gross errors associated with the VM-63-S induction watthour meter result from manufacturer's or test laboratory's calibration errors, failure to make necessary meter compensating adjustments for low power factor loads, failure to read and record data correctly and failure in computational analysis of data. For the VM-63-S meter used in Part II, the magnitude of the gross error is considered to be negligible unless specifically stated otherwise.

8.2 Systematic Errors

The systematic errors associated with the operation of the induction watthour meter are classified as a) instrumental errors and b) environmental errors

a) Instrumental Errors

Instrumental errors are inherent meter errors caused by:

- (1) instrument power losses
- (2) improper meter adjustments
- (3) changes in voltage
- (4) overload
- (5) changes in frequency
- (6) changes in waveform
- (7) changes in power factor
- (8) physical construction defects
- (9) ageing electrical and mechanical properties

The following is a discussion of instrumental errors that may be associated with the operation of the VM-63-S induction watt-hour meter.

(1) Instrument Power Loss

The instrument power losses associated with the VM-63-S watt-hour meter are a result of insertion losses due to the physical connections made by the voltage and current-coil circuits. Just like the P-3 wattmeter the two connections are the I^2R_C and V^2/R_V correction connections which are shown in figure 8.1(a) and 8.1(b). For the VM-63-S induction watt-hour meter the I^2R_C losses vary between 0 and 1.25 watts, while the V^2/R_V losses are constant at 93.5 watts. The large V^2/R_V loss results from the low voltage-coil resistance of 154 ohms and as a result the I^2R_C connection must be used to prevent large systematic error.

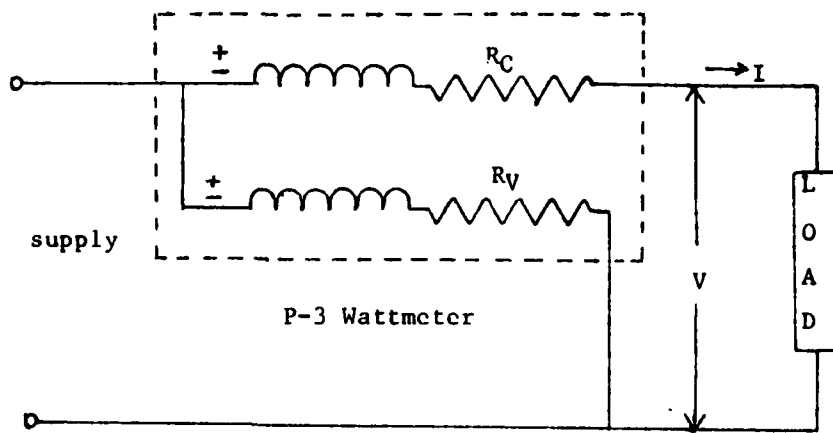


Figure 8.1(a) $I^2 R_C$ Correction Connection

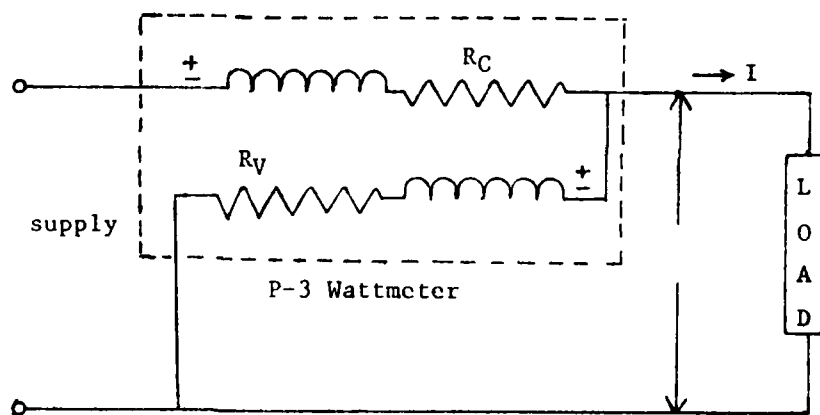


Figure 8.1(b) V^2 / R_V Correction Connection

(2) Improper Meter Adjustments

The correct operation of an induction watt-hour meter is dependent on three main adjustments. These adjustments are the full-load adjustment (also called the main speed adjustment), the light-load adjustment (also called the friction adjustment) and the inductive-load adjustment

(also called the lag adjustment). The full-load adjustment provides for the correct magnetic-breaking action to give the proper speed when the meter is operated at rated voltage and current at unity power factor. The full-load adjustment has approximately the same effect on meter operation at all loads. The light-load adjustment compensates for the effect of factors which have negligible effect at full load but would introduce appreciable error at light load. Some of these light load factors are friction, lack of linearity of driving torque with respect to load current and the existence of torques due to the potential flux alone. The light load adjustment results in a compensating torque which is constant. The effect of this adjustment on meter accuracy is inversely proportional to load. The inductive-load adjustment is used to provide the full 90 degree lag necessary between the voltage-coil flux and the line voltage to give correct measurement at all power factors. If this inductive-load adjustment is not properly made serious meter errors will result at power factors less than unity.

One last adjustment that needs to be made is for meter "creep" which causes the disk to rotate slowly at no load (zero current in current coil). This creep is usually caused by too large of a friction-compensating torque and is corrected for by drilling two small holes in the disk which open circuit the eddy currents in the disk which results in a small locking torque. The net effect of

improper meter adjustments for the induction watt-hour meter is that large errors will result in meter readings if the meter is improperly adjusted.

(3) Changes in Voltage

In theory an increase of the voltage applied to the voltage circuit should increase the driving torque proportionately; however, in practice an exactly proportional increase in disk speed will not occur for the following two reasons [23].

"(i) The braking torque in a meter is mainly produced by the cutting of the flux of the permanent magnet, but is partly due to cutting of the alternating fluxes of the voltage and current magnets. This is of little moment as long as these alternating fluxes are of constant rms value. Increase of the voltage flux clearly violates this condition and causes the meter to run slow. This effect is important at higher loads and is minimized by keeping the value of braking-magnet flux as high as possible in comparison with the voltage-magnet flux.

(ii) Increase of the voltage flux increases the friction-compensating torque produced by the voltage flux and tends to cause the meter to run fast. This is the more important effect at light loads."

The effect of changes in voltage is negligible providing these voltage changes are not large or frequently occurring.

(4) Overload

The term "overload" means that the current in the current coil, while not large enough to cause damage, is in excess of the rated current of the meter. Often under actual load conditions current in excess of rated current exists and the result is the meter tends to run slow due to saturation of the current magnet and the increase in the small braking torque produced by the flux of the current magnet. The effect of overload is negligible providing this condition does not exist for extended periods of time.

(5) Changes in Frequency

Changes in frequency from the calibrated value causes a variation in the reactance of the voltage-coil circuit and a variation in the amount of compensation in the phase compensating circuit. Under normal operation this frequency variation falls within a narrow range and is negligible for 60 Hz sinusoidal signals. When non-sinusoidal signals are encountered, the effects of frequency variations can be significant.

(6) Changes in Waveform

Since waveform variations are composed of several harmonics, the net effect is similar to frequency distortion where the inductive reactance of the current and voltage coils changes. This change in inductive reactance can cause a change in voltage and current-coil current and result in a greater phase displacement which affects the

torque developed and hence the power reading. The effects of non-sinusoidal signals on induction watt-hour meters can be significant and have been investigated [10,11,28,-29,35,36,37,38,39,40,41] and will be investigated more in the future as more power electronic devices impact on the power industry. Another characteristic of waveform distortion is the presence of a dc component which is not measured by an induction watt-hour meter. The net effect of this dc component on utility company billing has been investigated [10,11,38] but future impact will necessitate further analysis.

(7) Changes in Power Factor

Power factor errors are primarily caused by the inductive reactance of the voltage-coil circuit. As mentioned earlier, this inductive effect is compensated for by adjustment of the inductive-load adjustment. If the meter is properly calibrated and operated at power line frequency this effect should be negligible.

(8) Physical Construction Defects

Physical construction defects are normally a result of errors introduced in the manufacture of the meter. Some possible construction defects for an induction watt-hour meter might be defective bearings, bent shaft, warped disk, defective coils, or weak magnets. Normally for a new and calibrated meter these errors are negligible.

(9) Ageing Electrical and Mechanical Properties

The effects of ageing on the electrical properties

such as resistance and inductance is negligible for the induction watthour meter. The effects of ageing on the mechanical properties can be significant if the meter is not quality checked and calibrated on a regular basis. The induction watthour meter is subject to errors due to dust and dirt in the meter movement mechanism, worn or improperly aligned bearings, warped disk, defective coils, and weakened magnets. Also, the effect of vibration on the mechanical parts of a meter can be significant if the meter is improperly installed or subjected to vibrations for an extended period of time.

(b) Environmental Errors

Environmental errors that may adversely affect the induction watthour meter are:

- (1) ambient-temperature influence
- (2) self-heating influence
- (3) stray-field influence

The following is a discussion of environmental errors that may be associated with the operation of the VM-63-S induction watthour meter.

(1) Ambient-temperature influence

The effects of changes in ambient-temperature on the operation of an induction watthour meter are classified as Class I or Class II. Class I effects produce a change in speed and are independent of the power factor of the load being measured. The major influence of Class I effects is a change in strength of the braking magnets which will

normally cause the meter to run faster as temperature increases. Class II effects produce a change in speed and vary with the power factor of the load. The major influence of Class II effects is a change in phase angle between the potential flux and the current flux which is caused by a change in resistance of the potential-coil winding, a change in iron loss of the potential-coil core and a change in resistance of the lag plate and disk. The overall effect of ambient-temperature on the induction watt-hour meter normally is not significant. I was unable to find a specification that specified the change in accuracy per degree Centigrade change for the VM-63-S watt-hour meter.

(2) Self-heating Influence

The self-heating influence is caused by the temperature rise due to the I^2R or V^2/R losses of the instrument. For the VM-63-S meter the V^2/R loss is very large (93.5 watts) and necessitates using the I^2R connection. The overall effect of self-heating on the VM-63-S using the I^2R connection is negligible. I was unable to find a specification that specified the change in accuracy for the VM-63-S watt-hour meter.

(3) Stray-field Influence

The influence of stray fields on the operation of an induction watt-hour meter is normally considered negligible due to the high driving torque of the meter. If the stray fields are exceedingly strong, eddy currents can

be produced in the meter disk which react with the potential-coil flux to develop a torque which causes creeping.

8.3 Random Errors

The random errors associated with the operation of the VM-63-S induction wattmeter are unpredictable and probably would be a result of noise or transient over- or under-voltage conditions. Random errors are considered to be negligible unless specifically stated as an experimental variable in Part II of this thesis.

8.4 Limiting or Guarantee Error

As mentioned in Chapter 5, the VM-63-S induction watthour meter is subject to limiting or guarantee error. The limiting error or stated accuracy [reference ANSI Standard C12-1975] for the VM-63-S class 10 induction watthour meter is specified as a nominal manufacturer's accuracy [26] of ± 0.4 per cent of full-load current at a power factor of 1.0, and ± 1.0 per cent at full-load current at a power factor of 0.5 lagging, and ± 0.5 per cent at light-load (10 per cent of full load) current at a power factor of 1.0 for 60 Hz alternating current systems. The main difference in specifying limiting error for an induction watthour meter is that its per cent accuracy is expressed as a per cent of the reading and therefore has the same per cent error at low and high energy (power) readings.

8.5 Conclusions

The General Electric Type VM-63-S Induction Watthour Meter is the typical induction type of meter that is used in most industrial

applications for measuring energy usage. It is not designed to measure accurately energy (power) that has both an ac and a dc component, as the meter only responds to ac variations. Its ability to measure accurately non-sinusoidal power, especially power with a large dc component, is questionable. Extensive studies have been conducted by the Electric Power Research Institute (EPRI) [35] into the effects of harmonic distortion on the operation of the induction watthour meter and EPRI has concluded that the induction watthour meter does register within standards for power measurements at 60 Hz if the harmonic content is less than 3 per cent of the total power. EPRI goes on to conclude that the induction watthour meter does not accurately measure harmonic power content that exists in distorted current and voltage waveforms. Also, articles [28,29] indicated that an induction watthour meter used to measure SCR loads could have an accuracy of ± 10 per cent. These loads were a worst case condition and wouldn't necessarily occur under normal industrial loading.

The GE VM-63-S watthour meter is an accurate meter for measuring standard industrial 60 Hz measurements for both sinusoidal and nonsinusoidal applications. The effects of gross or human errors are kept to a minimum if good experimental technique is used. The effects of systematic errors due to changes in voltage, overload, and changes in power factor are negligible. Systematic errors due to changes in frequency and waveform can be significant with non-sinusoidal signals containing a high dc component. Systematic errors due to physical construction defects or due to the ageing of electrical and mechanical components can be minimized if regular calibration and maintenance is performed. Probably the two most significant sys-

tematic errors occur due to high insertion losses if proper correction factors are not used and due to improper meter adjustments if the meter is misaligned or miscalibrated. The effects of environmental errors on the induction watthour meter are considered to be negligible if operated in its normal temperature and current range and environment. The effects of random errors are unpredictable and are considered negligible. The effect of limiting or guarantee error is negligible because the meter accuracy is based on a per cent of the meter reading rather than a per cent of full scale.

PART II

TESTING AND EXPERIMENTAL WORK

CHAPTER 9

Pre-experimental Analysis and Test Procedures

This chapter sets forth the pre-experimental analysis that was done and the criteria used to determine the accuracy of the meters used in measuring single-phase power from a sinusoidal, a half-wave rectified and a bidirectional thyristor-controlled source. It discusses the experimental setup and procedures as well as the power correction factors used. It concludes by defining the characteristics of the various test loads.

9.1 Pre-experimental Analysis

Prior to doing the experimental work, it was necessary to establish procedures that would fairly compare the meters being tested under what would be their normal operating conditions. The types of meters tested were:

- a) two-General Electric, Type P-3 Electrodynamic Wattmeters
- b) two-Clarke-Hess, Model 255 Digital Wattmeters
- c) one-General Electric, Type VM-63-S, Class 10 Induction Watthour Meter.

A complete list of equipment used for the experimental work can be found in Appendix I.

It was decided that three common sources of power that all meters were expected to measure were the 120 volt, 60 Hz sinusoidal source, a half-wave rectified source and a bidirectional thyristor-

controlled source. It was also decided that the meters would be subjected to the following loading conditions:

- a) a high power-factor load (primarily resistive)
- b) a resistive-inductive (R-L) load
- c) a resistive-capacitive (R-C) load.

This varying load would subject the test meters to both a lagging and a leading power-factor.

In order to compare the meters, the following limitations were established:

- a) the total composite current was less than or equal to 5 amps.
- b) the total power measured was less than 1000 watts.
- c) the power factor of the circuit was varied between 0 and 1.00 (both lagging and leading).

The above limitations were primarily based on the limited current range of 5 amps of the Clarke-Hess (C.H.) meters and the requirement to measure within a power range, such that the electrodynamicometer (P-3) wattmeters would not incur gross errors due to the limited scale resolution of the P-3 meters at the low end. It was decided that based on a single-phase 120 volt source that the power range would vary between 0 to 600 watts. This power range was used primarily for comparing the P-3 and the C.H. meters. This power range was at the lower range of the VM-63-S induction watt-hour meter but later test results did not show this to be a problem except at power readings below 50 watts.

9.2 Criteria Used in Determining the Accuracy of the Power Measurement

The original idea was to do a comparison of the different types of meters, and to compare these results to a calculated power reading based on the voltage and current across a purely resistive load and to a graphical analysis method. Later experimental results, however, showed two significant problems that would make the later two methods for determining power less accurate than a comparative analysis of meters approach. The first problem came from the fact that a purely resistive-load was not available for the power and current ranges desired. As can be seen in section 9.5, the actual characteristics of the high power-factor load contained a significant amount of inductance. Also it was found that depending on the way the load was dialed into the circuit (crude adjustment or load potentiometer) or depending on how much of each resistance load was used that a considerable difference in inductance resulted. The problem of trying to calculate power based on the voltage, current and power factor of the load grew worse when additional inductance (R-L load) and additional capacitance (R-C load) was added to the high power-factor load. An additional problem in trying to compute a calculated value of power based on the voltage, current and power factor of the load is the guarantee error associated with each measuring meter. Therefore, this method of computing power was eliminated, as the accuracy of this method was suspect for the above listed reasons. The second problem came from trying to apply a graphical analysis method. After the tests were performed, the test data on the P-3 and C.H. meters varied normally by only ± 3.0 per cent. It was decided that due to the

inherent inaccuracies of the graphical analysis method because of scope and probe attenuation, because of variations in shunt and load resistance, and because of computational error and inaccuracy, that the graphical method would not be used.

Since both the calculated power method ($V_L \times I_L \times \cos \theta$) and the graphical analysis method proved insufficient for the type of accuracy desired, and since no primary or absolute standard was available, it was decided that a comparative method using the P-3 meters as the reference standard was the best approach in determining the relative power reading being measured. This comparative method was not expected to give an absolute value of power but to show how a comparative range or relative degree of uncertainty exists in similar types of power measurements using these types of meters.

9.3 Experimental Setup and Procedures

Experimental Setup

The experimental setup designed for measuring single-phase power is shown in figures 9.1 and 9.2. Figure 9.1 shows that a standard 120 V 60 Hz source is being fed to the power and energy meters. The output of the meters are fed to the specific test source (either ac, half-wave rectified, or thyristor-controlled) and from this source to the test load. A shunt with cathode-ray-oscilloscope is used to maintain a visual presentation of what is happening in the circuit. Figure 9.2 is the actual wiring diagram used for all testing. A switching arrangement is used for the various power and energy meters to provide isolation of each meter when measuring power and to limit the loading effect of each meter. This arrangement worked very well throughout the experimental process.

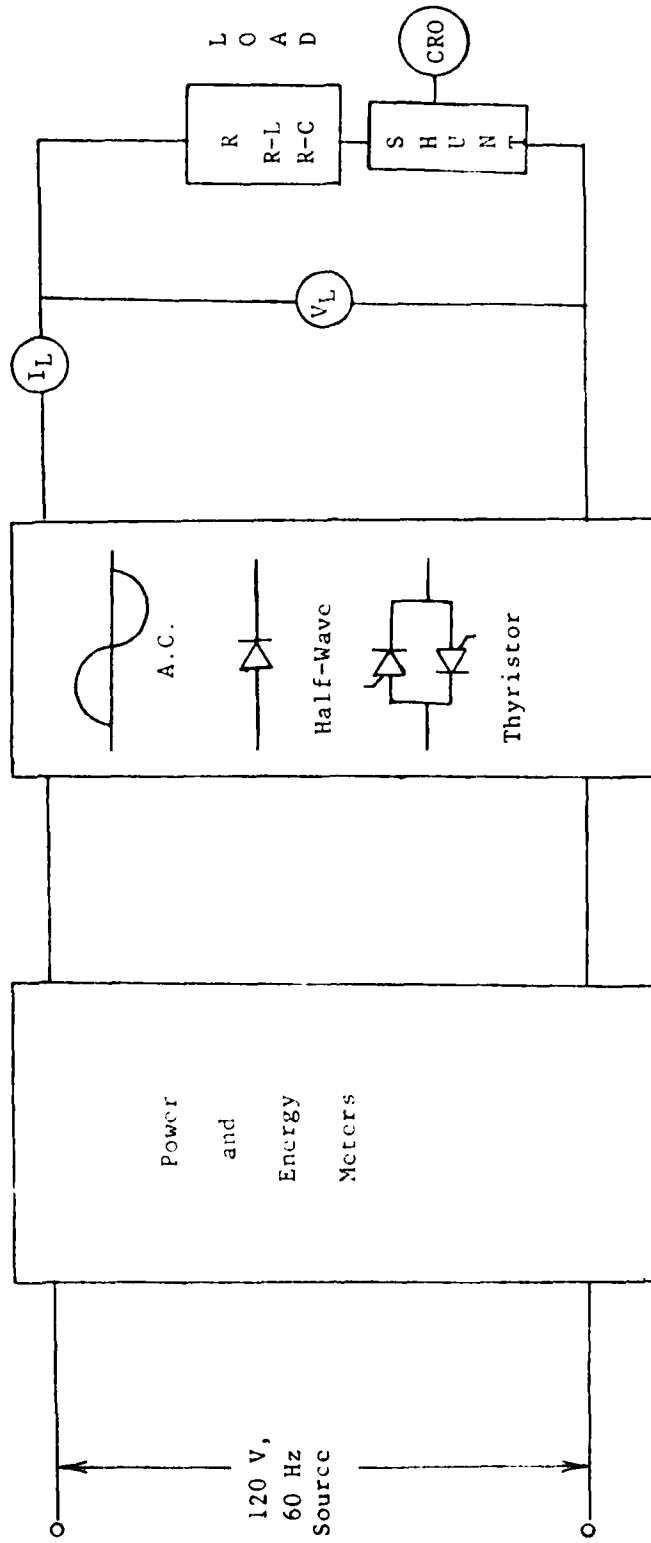


Figure 9.1 Block Diagram of Experimental Setup

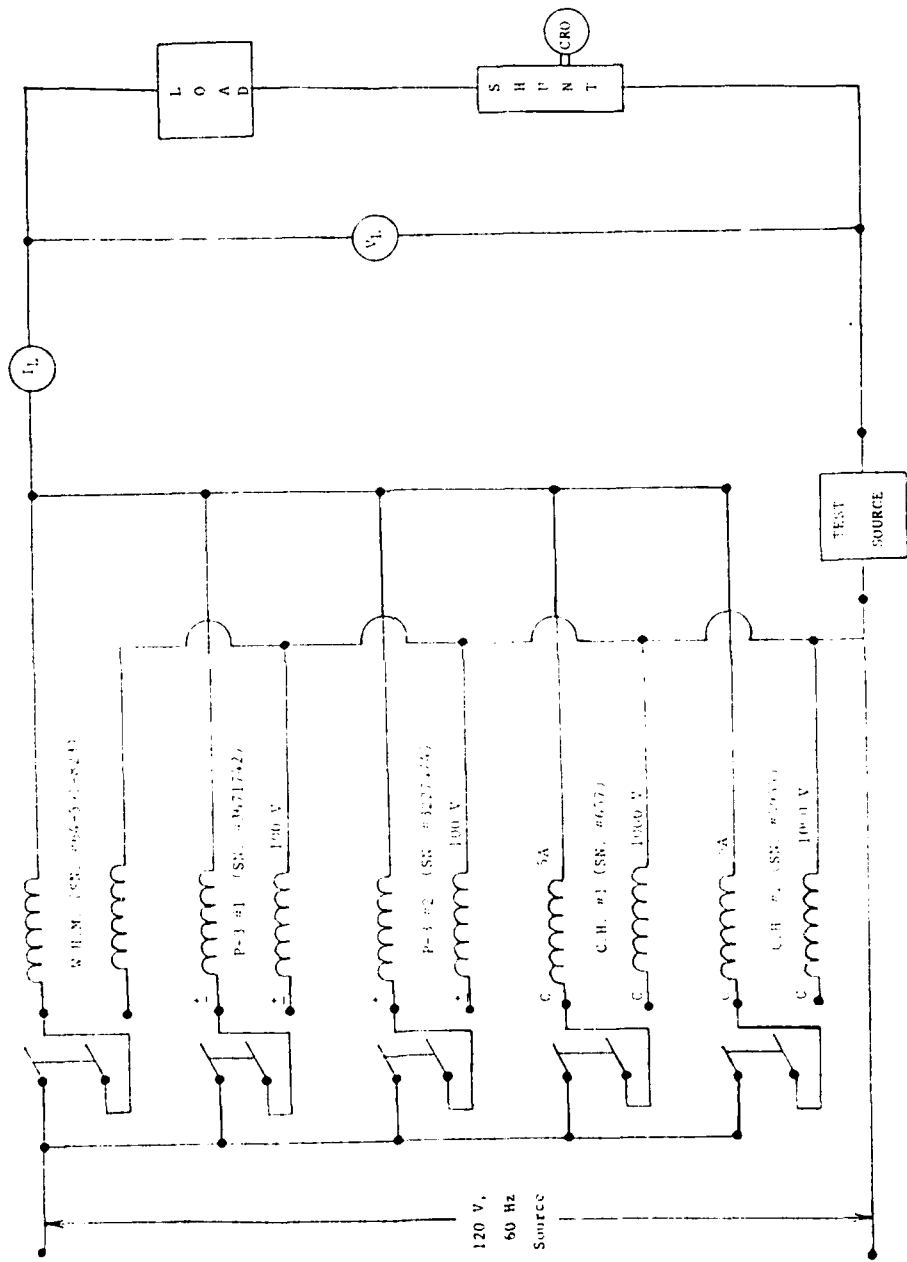


Figure 9.2 Schematic Diagram of Experimental Setup

It should be pointed out that all power and energy measurements were made at the line side of the test source. For this reason the voltage coil of all the measuring devices was always subjected to a sinusoidal voltage signal. Also as a result of this line side measurement the only nonsinusoidal circuit variation would occur in the current waveform. The line side measurements were used primarily because this would be the normal configuration for the induction watt-hour meter (W.H.M.).

Experimental Procedures

The experimental procedures consisted of varying each load with each test source and measuring the power. The 120 V, 60 Hz source and the half-wave rectified source were direct in-line sources. The bidirectional thyristor-controlled (triac) source was fabricated earlier during work on a special research project for the U.S. Army (contract number DAAK 70-80-C-0136). The test loads consisted of a high power-factor load (0-240 ohms of resistance and 0 to 100 ohms of inductive reactance), a resistive-inductive load (high power-factor load plus a 65 milli-henry inductance), and a resistive-capacitive load (high power-factor load plus a 140 micro-farad capacitance).

The test procedures consisted of selecting a source and load, varying the current from 0 to 5 amps and measuring individually the circuit power with each meter. In the case of the W.H.M., a counter network was devised to measure the number of disk revolutions. This counter circuit is shown in figure 9.3.

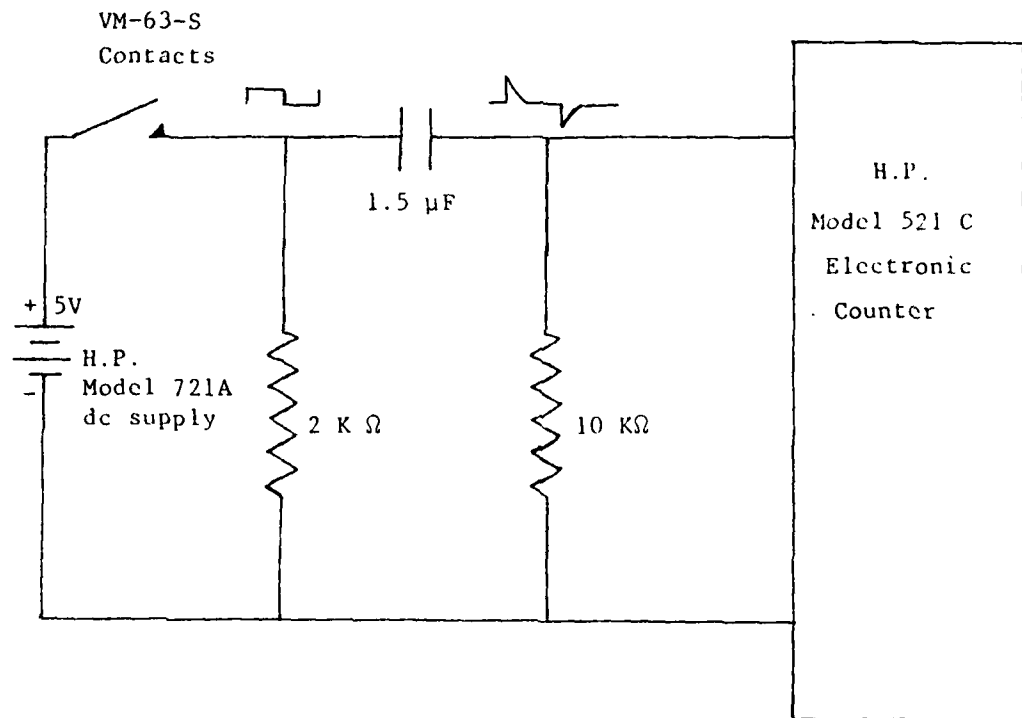


Figure 9.3 Counter Network Used With the W.H.M.

The average power of the circuit, when using the W.H.M. was measured by counting the number of disk revolutions in a specified period of time. The average power of the circuit was calculated by the following equation

$$P_{AVG} = \frac{Kh}{2} \times 3600 \times \text{COUNT} \times \frac{1}{t} \quad (9.1)$$

where Kh = is the watt-hour constant = 2.4

t = time in seconds

Equation 9.1 can be further simplified to the following:

$$P_{AVG.} = 4320 \times \frac{\text{COUNT}}{t_{SEC}} \quad (9.2)$$

Note: In order to be able to compare the W.H.M. power readings with the P-3 and C.H. power readings it is essential that the load be maintained constant for the measuring time interval. Power readings were taken with the C.H. wattmeters both before and after the readings were completed using the W.H.M. No large changes between these initial and final power readings were observed, thus the comparison of W.H.M. to the P-3 and C.H. meters are fair comparisons. It is also realized, however, that some load variation did exist with time and as a result some error may be introduced in this comparison, especially at low power measurements. This change in load with respect to time was partially offset by reducing the time interval and measuring time in tenths of a second versus measuring time in seconds.

9.4 Power Correction Factors

As mentioned in Chapters 6, 7 and 8, all three meters are subject to instrumental error due to instrument power loss caused by the loading effect of the meters. This instrument power loss causes the meters to read high for both the I^2R_S and the V^2/R_V connections. As a result of this instrumental power loss all measured raw data was converted to a power corrected ($P_{CORR.}$) value. This corrected value was used for the comparisons between meter types. The actual power correction factors used for each meter at the various current ranges

and for the various connections are shown in Table 9.1. The I^2R_S correction term was used for all meters as this was the actual test configuration used.

9.5 Characteristics of Various Test Loads

The test loads used in the experimental work consisted of the following:

- a) a high power-factor load (0-240 ohms of resistance and 0-100 ohms of inductive reactance)
- b) a resistive-inductive (R-L) load (the high power-factor load plus a 65 milli-henry series inductance)
- c) a resistive-capacitive (R-C) load (the high power-factor load plus a 140 micro-farad series capacitance).

The test loads were selected so that the test meters would be subjected to both a lagging and a leading power factor and so that the range in power factor would vary considerably from 0 to 1.00.

The major problem with the load characteristics was with the high power-factor load. Ideally, this load was desired to be purely resistive but because the load resistance was actually wrapped in coils on an insulator an actual inductance value as great as 266 milli-henrys was observed. The data taken in determining the actual load characteristics is given in Table 9.2 and a plot of the actual load inductance for the high power-factor load is shown in figure 9.4. A further complication with determining the actual load characteristics of the high power-factor load resulted from the actual experimental procedure used in dialing the various resistive loads (crude adjustment on load potentiometer) into the circuit. It was found that,

Table 9-1

Correction Factors for Power Measurements

I _L (AMPS)	P-3			C.H.		W.H.M	
	I ² R _S (5A)	I ² R _S (10A)	V ² /R _V (100V)	I ² R _S (5A)	V ² /R _V (200V)	I ² R _S	V ² /R _V
0	--	--	--	--	--	--	--
0.50	0.02	0.01	1.31	0.01	0.01	0.01	93.5
1.00	0.08	0.02	1.31	0.03	0.01	0.05	93.5
1.50	0.18	0.05	1.31	0.06	0.01	0.11	93.5
2.00	0.32	0.08	1.31	0.11	0.01	0.20	93.5
2.50	0.50	0.13	1.31	0.18	0.01	0.31	93.5
3.00	0.72	0.18	1.31	0.25	0.01	0.45	93.5
3.50	0.98	0.25	1.31	0.34	0.01	0.61	93.5
4.00	1.28	0.32	1.31	0.45	0.01	0.80	93.5
4.50	1.62	0.41	1.31	0.57	0.01	1.01	93.5
5.00	2.00	0.50	1.31	0.70	0.01	1.25	93.5

Table 9.2

Determining Actual Inductance and Load Characteristics
for a High Power Factor Load Using a Sinusoidal Source

I _L (AMPS)	V _L (VOLTS)	C. H #1					R _{LDC} (OHMS)	Z _L CAL (OHMS)	L _L CAL (m H)
		I (AMPS)	V ₂₀₀ (VOLTS)	P ₂₀₀ (WATTS)	PF ₂₀₀				
0.46	111.8	0.44	112.0	49	0.898	238.0	258.3	266	
0.50	111.7	0.48	111.9	52	0.905	214.0	223.4	170	
0.75	111.6	0.74	111.7	80	0.918	129.9	148.8	193	
1.00	111.2	1.00	111.6	108	0.923	90.4	111.2	172	
1.21	111.0	1.21	111.5	130	0.920	75.3	91.7	139	
1.48	110.9	1.48	111.5	161	0.922	63.7	74.9	105	
1.75	110.4	1.76	111.1	191	0.928	52.5	63.1	92	
2.02	110.2	2.03	111.1	221	0.934	47.7	54.6	70	
2.24	109.9	2.26	110.8	245	0.938	42.8	49.1	65	
2.47	109.5	2.49	110.6	273	0.942	39.6	44.3	55	
3.02	109.2	3.05	110.4	334	0.953	33.2	36.2	38	
3.46	108.7	3.49	110.2	383	0.963	30.1	31.4	24	
3.98	108.4	4.01	110.0	442	0.974	26.7	27.2	14	
4.47	107.6	4.51	109.3	496	0.983	24.3	24.1	--	
4.68	107.5	4.72	109.3	518	0.986	23.2	23.0	--	
4.88	107.0	4.94	109.0	539	0.988	22.3	21.9	--	
---	---	--	---	---	---	---	---	--	
4.55	109.0	4.60	110.7	507	0.982	23.9	24.0	6	
4.95	108.1	5.01	110.3	552	0.988	22.2	21.8	--	

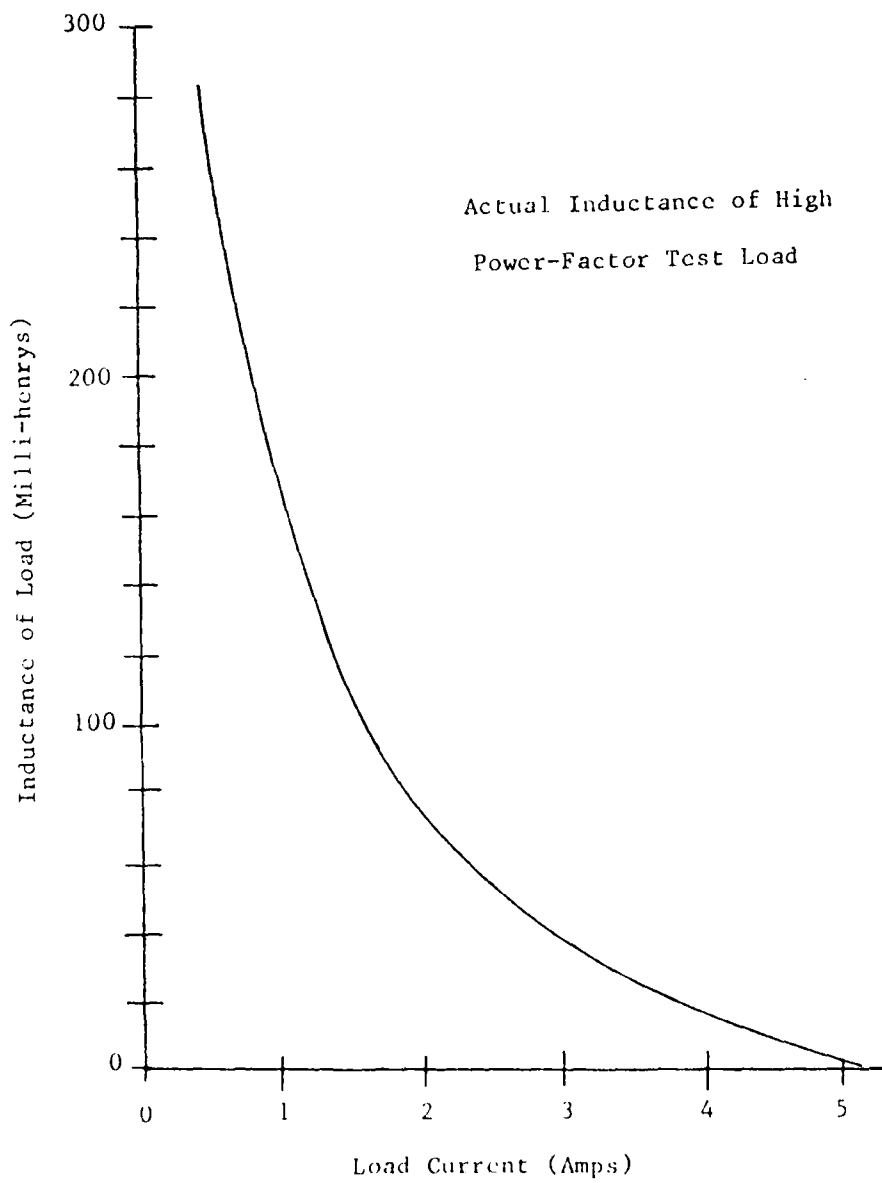


Figure 9.4 Actual Inductance of High Power-Factor Test Load

depending on how much of each resistive load was used in the circuit, a considerable difference in inductance could result. Because of this nonlinearity of the resistive loads it was necessary to establish a test procedure where the high power-factor load was varied the same (removing one load resistance at a time in the same order each time) for each test setup. The resulting inductance curve for this setup is shown in figure 9.4.

The test R-L load consisted of the high power-factor and the load in series with an inductance of approximately 65 milli-henrys and the test R-C load consisted of the high power-factor load in series with a capacitance of approximately 140 micro-farads. These test loads did not present any problems in the experimental work as did the high power-factor load mentioned previously.

CHAPTER 10

MEASURING SINGLE-PHASE POWER USING A SINUSOIDAL SOURCE

This chapter discusses the experimental results obtained using a sinusoidal source with a high power-factor load, a R-L load and a R-C load. It draws individual conclusions for each type of load by comparing the power readings by meter types and by comparing the average power readings of the P-3 meters, the C.H. meters and the W.H.M. The chapter concludes by summarizing the conclusions obtained using the sinusoidal source with the various loads.

10.1 High Power-Factor Load Test

This test was conducted using a sinusoidal source and the high power-factor load. The results of this test are as follows:

a) Comparison of Power Readings by Meter Types

(reference tables 10.1 and 10.2)

- (1) The P-3 meter readings were within ± 2 per cent of each other for all power measurements.
- (2) The C.H. meter readings were within ± 3 digits and ± 3 per cent of each other for all power measurements except at the low power measurement of 56 watts.
- (3) A comparison of C.H. meters, measuring power on the P₂₀₀ and P₁₀₀₀ ranges resulted in a difference of less than ± 2 per cent. This indicated that either scale could be used for measuring power. The P₂₀₀ range was used for the remainder of the experiments as the P₁₀₀₀ range gave con-

sistently higher readings than the P₂₀₀ range and because the P₂₀₀ range was closer to the values measured by the P-3 meters. Note: the P₂₀₀ and P₁₀₀₀ measurements are based on the voltage selection switch settings of V₂₀₀ and V₁₀₀₀. There is no actual P₂₀₀ and P₁₀₀₀ setting on the C.H. meters.

- (4) The expanded scale (Px10) for the C.H. meters is only guaranteed accurate at current and voltage values of less than 40 per cent of the current and voltage switch settings. The values of Px10 readings for currents greater than 2.0 amps became suspect. The data from table 10.1 indicates clearly how gross errors can occur if one tries to use the expanded scale outside its specified range. The maximum error for using the expanded scale (Px10) outside its specified range ("INPUT OVERLOAD" light ON) was a -9.2 per cent at the 5 amp value. Note: the "INPUT OVERLOAD" light is an indicating L.E.D. that indicates that the peak input levels exceed the dc set points. The brightness of the L.E.D. indicator gives an indication of how long the input signals are spending in the overload region.

b) Comparison of Average Power Readings (reference table 10-3)

- (1) The C.H. AVG. power readings were between 1 and 3 per cent higher than the P-3 AVG. readings.
- (2) The W.H.M. average power readings were between 0 to 3 per cent lower than the P-3 AVG. readings with the exception of one reading at the 1.00 amp setting.

10.2 Resistive-Inductive (R-L) Load Test

This test was conducted using a sinusoidal source and the high power-factor load in series with a 65 milli-henry inductance. The results of this test are as follows:

a) Comparison of Power Readings by Meter Types

(reference tables 10-4 and 10-5)

- (1) The P-3 meter readings were within ± 2 per cent of each other for all power measurements except for one reading at the low power measurement of 43.2 watts.
- (2) The C.H. meter readings were within ± 2 digits and ± 2 per cent for all power measurements taken up to the 4.00 amp setting. At current values greater than 4.00 amps, C.H. #1 was affected significantly by the decrease in power-factor due to the increase in inductance. At a power-factor less than 0.500, the variation between C.H. #1 and C.H. #2 became significant and resulted in a maximum difference of 12.7 per cent at the 4.80 setting. Note: C.H. #2 meter behaved very similarly to the P-3 meters.

b) Comparison of Average Power Readings (reference table 10-6)

- (1) The C.H. AVG. power readings were between 0 to 2 per cent higher than the P-3 AVG. readings for values up to 4.00 amps. At values greater than 4.00 amps this difference increased to 4 per cent higher due to the increase power readings of C.H. #1.
- (2) The W.H.M. average power readings were generally between 3 to 7 per cent lower than the P-3 AVG. readings for all values except at the low power readings of 52.5 and 44.5

watts. At these low power readings the W.H.M. indicated a significantly smaller reading of 11.2 and 19.6 per cent lower than the P-3 AVG. These lower readings were a result of the increased circuit inductance and a correspondingly lower power-factor at these low power readings. Note: These values at low power are approximately 10 per cent lower than for the high power-factor load of table 10-3.

10.3 Resistive-Capacitive (R-C) Load Test

This test was conducted using a sinusoidal source and the high power-factor load in series with a 140 micro-farad capacitance. The results of this test are as follows:

a) Comparison of Power Readings by Meter Types

(reference tables 10-7 and 10-8)

- (1) The P-3 meter readings were within ± 2 per cent of each other for all power measurements except for one reading at the low power measurement of 55 watts.
- (2) The C.H. meter readings were within ± 2.5 digits and ± 3 per cent for all power measurements.
- (3) A comparison of C.H. meters indicated a similar comparison to the high power-factor load of table 10-2.

b) Comparison of Average Power Readings (reference table 10-9)

- (1) The C.H. AVG. power readings ranged from 1 per cent lower to 3 per cent higher than the P-3 AVG. readings.
- (2) The W.H.M. average power readings ranged from 9 per cent lower to 1 per cent higher than the P-3 AVG. readings. The W.H.M. showed a tendency to increase in value compared

to the P-3 AVG. readings as the capacitive reactance became a more significant part of the circuit load. This increase in power readings of the W.H.M. is due to the phase-angle decreasing between the voltage and current components which results in a higher net power reading.

10.4 Conclusions

The results of using a sinusoidal source and varying the loading with both a leading and lagging power-factor and measuring the average power with the P-3's, the C.H.'s and the W.H.M. are as follows:

- a) The P-3 wattmeter readings were generally within ± 2 per cent of each other for all types of loads. The P-3 meters did not seem to be affected by power-factor variations. This result agrees with reference 21, as the P-3 wattmeter reading is expected to be the same regardless of leading or lagging power-factor circuit conditions, since the average torque and average power is a result of the instantaneous product of voltage and current. The effect of limiting error on the P-3 wattmeter is only significant at low power readings (below 50 watts) and this effect was confirmed by the test results.
- b) The C.H. wattmeter readings were generally within ± 3 digits or ± 3 per cent of each other for all types of loads. The only significant difference occurred with C.H. #1 when measuring the R-L load at current values above 4.00 amps. The test data of tables 10-5 and 10-6 indicate that C.H. #1 was affected by changes in power-factor, especially at a lagging power-factor

of 0.112 where the per cent difference between C.H. #1 and either C.H. #2 or the P-3 meters increased to + 13 per cent. Generally, the C.H. meter readings were within ± 3 per cent of the P-3 meter readings for all tests performed in this chapter.

- (c) The C.H. meters have the capability of measuring power on several scales (P₂₀₀, P₁₀₀₀ and P_{x10}) and the experimental data showed less than a 2 per cent difference between different scale measurements. It was also found that the "INPUT OVERLOAD" condition would result if either current or voltage values were exceeded on any scale. The result of an Input Overload condition on the P_{x10} scale resulted in a gross error of -10 per cent for the test performed on the high power-factor load.
- d) The W.H.M. readings compared to the P-3 AVG. wattmeter readings varied considerably depending on the type of load. For the high power-factor load, the variation between the W.H.M. and the P-3 AVG. reading ranged from 0 to 3 per cent lower. For the R-L load, the variation between the W.H.M. and the P-3 AVG. reading was generally lowered an additional 3 percent and the range of this variation was between -3 to -7 per cent. This increased difference was a result of the increased inductance in the circuit which caused a considerable lagging power factor. This lagging power-factor also had a significant effect at low power readings as the difference between the W.H.M. and the P-3 AVG. reading increased

to -11 and -19.6 per cent. This difference may have been partially due to operating at the low end of the W.H.M. but test data on the high power-factor load only resulted in a 3 per cent difference at this same low power reading. For the R-C load, the variation between the W.H.M. and the P-3 AVG. reading varied between a -9 per cent to a +1 per cent. Again this result indicated that the W.H.M. is affected by power-factor. The effect of increasing capacitive reactance was that the W.H.M. reading was greater than the P-3 AVG. reading. This speeding up of the W.H.M. occurs with a capacitive load, as a similar result occurred on the thyristor-controlled R-C load test (see table 12-9).

Table 10.1

Determining Meter Characteristics and Measuring Single-Phase Power for a High Power-Factor Load Using a Sinusoidal Source

I _L (AMPS)	V _{AMP} (VOLTS)	V _L (VOLTS)	P-3 #1		P-3 #2		C.H. #1						
			MEAS. (WATTS)	CORR. (WATTS)	MEAS. (WATTS)	CORR. (WATTS)	I ₅ (AMPS)	V ₂₀₀ (VOLTS)	P ₂₀₀ (WATTS)	P ₁₀₀₀ (WATTS)	P _{x10} (WATTS)	P _{CORR.} (WATTS)	PF ₂₀₀
0	0.00	0.0	0	--	0	--	0.00	0.00	0.00	0.0	00.1	--	--
0.50	0.06	119.0	56.0	56.0	55.5	55.5	0.48	119.1	56	57.0	56.3	56.0	0.904
1.00	0.19	118.2	113.5	113.4	114.5	114.4	0.99	118.4	115	116.0	114.9	115.0	0.919
1.50	0.29	118.7	171.5	171.3	172.0	171.8	1.50	119.1	174	176.0	173.6	173.9	0.922
2.00	0.31	118.1	228.0	227.7	231.0	230.7	2.00	118.5	232	234.5	233.3	231.9	0.932
2.50	0.40	117.5	284.5	284.0	289.0	288.5	2.52	118.1	291	294.0	292.4	290.8	0.942
3.00	0.51	117.3	342.0	341.3	347.0	346.3	3.02	118.0	350	355.0	350.8	349.8	0.954
3.50	0.59	117.1	399.5	398.5	404.5	403.5	3.54	118.1	410	415.0	406.8	409.7	0.962
4.00	0.65	116.9	457.0	455.7	462.0	460.7	4.03	118.3	471	476.0	455.8	470.5	0.973
4.50	0.75	116.6	520.0	519.6	524.0	523.6	4.56	117.9	533	539.0	501.2	532.4	0.982
5.00	0.85	116.3	573.0	572.5	580.0	579.5	5.07	117.7	589	597.5	538.3	588.3	0.989

Table 10.1 (continued)

I5 (AMPS)	C.H. #2						W. H. M.				
	V200 (VOLTS)	P200 (WATTS)	P1000 (WATTS)	Px10 (WATTS)	PCORR. (WATTS)	P.F.200	t ₀ (SEC)	t _{final} (SEC)	Count	PCAL (WATTS)	PCORR. (WATTS)
0.00	0.00	0.0	0.00	00.0	--	--	--	--	--	--	--
0.50	118.8	58	59.5	56.5	58.0	0.901	0	797	10	54.2	54.2
1.00	118.1	118	119.5	115.2	118.0	0.935	0	404	10	106.9	106.9
1.50	118.9	176	178.0	173.8	175.9	0.939	0	259	10	166.8	166.7
2.01	117.8	233	233.5	232.2	232.9	0.947	0	192	10	225.0	224.8
2.51	117.8	293	293.0	291.5	292.8	0.957	0	154	10	280.5	280.2
3.02	117.9	352	351.0	349.3	351.8	0.965	0	128	10	337.5	337.1
3.53	117.8	412	409.0	406.6	411.7	0.973	0	108	10	400.0	399.4
4.02	118.1	471	466.0	455.5	470.5	0.982	0	96	10	450.0	449.2
4.53	117.6	531	524.5	499.3	530.4	0.990	0	85	10	508.2	507.2
5.04	117.5	585	577.0	531.3	584.3	0.994	0	77	10	561.0	559.8

NOTES:

- 1) PCORR. for C.H. #1 and C.H. #2 are corrected for the P200 power reading.
- 2) xxxx for C.H. #1 and C.H. #2 for the P x 10 readings are in error ("input overload" light lit) but were taken for comparative analysis.
- 3) xxxx for P-3 #1 and P-3 #2 measured power readings were taken at 10 amp setting rather than 5 amp setting.

Table 10-2
 Comparison of Power Readings by Meter Types
 for a High Power Factor Load Using a Sinusoidal Source

I _L (AMPS)	P-3 #1		P-3 #2		C.H. #1		C.H. #2	
	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)
0.50	+0.5	+0.9	--	--	--	--	+2.0	+3.6
1.00	--	--	+1.0	+0.9	--	--	+3.0	+2.6
1.50	--	--	+0.5	+0.3	--	--	+2.0	+1.1
2.00	--	--	+3.0	+1.3	--	--	+1.0	+0.4
2.50	--	--	+4.5	+1.6	--	--	+2.0	+0.7
3.00	--	--	+5.0	+1.5	--	--	+2.0	+0.6
3.50	--	--	+5.0	+1.3	--	--	+2.0	+0.5
4.00	--	--	+5.0	+1.1	--	--	--	--
4.50	--	--	+4.0	+0.8	+2.0	+0.4	--	--
5.00	--	--	+7.0	+1.2	+4.0	+0.7	--	--

Table 10-3
 Comparison of Power Readings for a High Power-Factor Load Using a Sinusoidal Source

I _L (AMPS)	P-3		C.H.			W.H.M.		
	AVG. (WATTS)		AVG. (WATTS)	DIFF. (WATTS)	DIFF. (%)	(WATTS)	DIFF. (WATTS)	DIFF. (%)
0.50	55.7		57.0	+ 1.3	+2.3	54.2	- 1.5	-2.7
1.00	113.9		116.5	+ 2.6	+2.3	106.9	- 7.0	-6.1
1.50	171.6		175.0	+ 3.4	+2.0	166.7	- 4.9	-2.9
2.00	229.2		232.4	+ 3.2	+1.4	224.8	- 4.4	-1.9
2.50	286.3		291.8	+ 5.5	+1.9	280.2	- 6.1	-2.1
3.00	343.8		350.7	+ 6.9	+2.0	337.1	- 6.7	-1.9
3.50	401.0		410.7	+ 9.7	+2.4	399.4	- 1.6	-0.4
4.00	458.2		470.5	+12.3	+2.7	449.2	- 9.0	-2.0
4.50	521.6		532.0	+10.4	+2.0	507.2	-14.4	-2.8
5.00	576.0		586.3	+10.3	+1.8	559.8	-16.2	-2.8

Table 10-4
 Measuring Single-Phase Power for a
 Resistive-Inductive (R-L) Load Using a Sinusoidal Source

I _L (AMPS)	V _{LOAD} (VOLTS)	V _{IND} (VOLTS)	P-3 #1		P-3 #2		C.H. #1			C.H. #2		W.H.M.	
			CORR. (WATTS)	CORR. (WATTS)	CORR. (WATTS)	I ₅ (AMPS)	V ₂₀₀ (VOLTS)	P.F. 200	P ₂₀₀ CORR.	P ₂₀₀ CORR.	P ₂₀₀ CORR.	P _{CORR.} (WATTS)	P _{CORR.} (WATTS)
0	00.0	0	0	0	0	0.00	0.00	--	--	0.00	--	--	--
0.50	105.8	13.7	53.0	52.0	52.0	0.49	111.2	0.870	52.0	53.0	46.6	53.0	46.6
1.00	100.4	25.5	99.4	100.4	100.4	1.00	110.9	0.863	100.0	101.0	93.4	101.0	93.4
1.51	94.5	37.2	145.3	145.8	145.8	1.52	110.4	0.835	145.9	146.9	139.3	146.9	139.3
2.01	89.5	48.7	184.2	185.7	185.7	2.03	110.8	0.806	187.9	188.9	179.8	188.9	179.8
2.53	83.0	60.6	218.0	221.5	221.5	2.55	110.7	0.765	222.8	224.8	211.5	224.8	211.5
3.04	76.5	72.1	246.3	248.8	248.8	3.09	110.7	0.720	250.2	250.7	235.5	250.7	235.5
3.32	72.5	78.2	256.0	258.5	258.5	3.35	110.5	0.693	261.7	260.7	247.8	260.7	247.8
3.50	67.7	82.4	253.5	257.0	257.0	3.55	110.2	0.657	259.7	259.7	244.9	259.7	244.9
4.00	42.4	93.3	233.2	235.2	235.2	4.05	110.3	0.533	238.5	237.5	224.2	237.5	224.2
4.25	42.7	99.0	208.5	209.5	209.5	4.32	110.7	0.445	214.0	209.5	199.1	209.5	199.1
4.50	28.9	104.3	160.9	160.9	160.9	4.58	110.6	0.337	168.4	163.4	153.3	163.4	153.3
4.75	8.6	109.7	79.2	77.7	77.7	4.80	110.9	0.158	81.3	76.8	75.8	76.8	75.8
4.80	1.5	111.2	45.7	43.2	43.2	4.88	111.7	0.112	48.8	43.3	35.8	43.3	35.8

Table 10-5

Comparison of Power Readings by Meter Types
for R-L Load Using a Sinusoidal Source

I _L (AMPS)	P-3 #1		P-3 #2		C.H. #1		C.H. #2	
	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)
0.50	+1.0	+1.9	--	--	--	--	+1.0	+1.9
1.00	--	--	+1.0	+1.0	--	--	+1.0	+1.0
1.51	--	--	+0.5	+0.3	--	--	+1.0	+0.7
2.01	--	--	+1.5	+0.8	--	--	+1.0	+0.5
2.53	--	--	+3.5	+1.6	--	--	+2.0	+0.9
3.04	--	--	+2.5	+1.0	--	--	+0.5	+0.2
3.32	--	--	+2.5	+1.0	+1.0	+0.4	--	--
3.50	--	--	+3.5	+1.4	--	--	--	--
4.00	--	--	+2.0	+0.9	+1.0	+0.4	--	--
4.25	--	--	+1.0	+0.5	+4.5	+2.1	--	--
4.50	--	--	--	--	+5.0	+3.1	--	--
4.75	+1.5	+1.9	--	--	+4.5	+5.9	--	--
4.80	+2.5	+5.8	--	--	+5.5	+12.7	--	--

Table 10-6
 Comparison of Power Readings for a R-L Load Using a Sinusoidal Source

I _L (AMPS)	P-3		C.H.			W.H.M.		
	AVG. (WATTS)	AVG. (WATTS)	DIFF. (WATTS)	DIFF. (%)	(WATTS)	DIFF. (WATTS)	DIFF. (%)	
0.50	52.5	52.5	0	0	46.6	- 5.9	-11.2	
1.00	99.9	100.5	+0.6	+0.6	93.4	- 6.5	- 6.5	
1.51	145.9	146.4	+0.5	+0.3	139.3	- 6.6	- 4.5	
2.01	185.0	188.4	+3.4	+1.8	179.8	- 5.2	- 2.8	
2.53	219.8	223.8	+4.0	+1.8	211.5	- 8.3	- 3.8	
3.04	247.6	250.5	+2.9	+1.2	235.5	-12.1	- 4.9	
3.32	257.3	261.2	+3.9	+1.5	247.8	- 9.5	- 3.7	
3.50	255.3	259.7	+4.4	+1.7	244.9	-10.4	- 4.1	
4.00	234.2	238.0	+3.8	+1.6	224.2	-10.0	- 4.3	
4.25	209.0	211.8	+2.8	+1.3	199.1	- 9.9	- 4.7	
4.50	160.9	165.9	+5.0	+3.1	153.3	- 7.6	- 4.7	
4.75	78.5	79.1	+0.6	+0.8	75.8	- 2.7	- 3.4	
4.80	44.5	46.1	+1.6	+3.6	35.8	- 8.7	-19.6	

Table 10-7

Measuring Single-Phase Power for a Resistive-Capacitive Load Using a Sinusoidal Source

I_L (AMPS)	V_{LOAD} (VOLTS)	V_C (VOLTS)	P-3 #1		P-3 #2		C.H. #1				C.H. #2		W.H.M.		
			CORR. (WATTS)	CORR. (WATTS)	CORR. (WATTS)	CORR. (WATTS)	I_5 (AMPS)	V_{200} (VOLTS)	P.F. 200	P200 CORR.	P200 CORR.	P200 CORR.	P200 CORR.	P CORR. (WATTS)	P CORR. (WATTS)
0	0.0	00.0	0	0	0	0.00	0.00	--	--	--	--	--	--	--	--
0.50	114.7	8.3	56.0	54.0	54.0	0.48	113.8	0.917	54.5	56.0	56.0	50.0	50.0	50.0	50.0
0.78	115.1	13.5	86.9	84.9	84.9	0.76	113.7	0.933	86.0	88.0	88.0	80.4	80.4	80.4	80.4
0.99	115.3	17.4	110.4	109.4	109.4	0.97	113.7	0.934	110.0	112.5	112.5	104.0	104.0	104.0	104.0
1.53	114.6	27.4	169.8	168.8	168.8	1.52	113.4	0.934	171.9	173.9	173.9	164.4	164.4	164.4	164.4
2.03	111.7	36.9	227.7	223.7	223.7	2.03	113.1	0.934	225.9	227.9	227.9	218.2	218.2	218.2	218.2
2.50	107.6	45.9	266.5	269.0	269.0	2.54	112.7	0.924	273.8	275.8	275.8	266.7	266.7	266.7	266.7
2.99	101.7	54.9	302.3	306.8	306.8	3.00	112.5	0.900	308.7	311.2	311.2	301.2	301.2	301.2	301.2
3.52	92.6	64.8	328.5	331.0	331.0	3.53	112.2	0.837	335.7	336.7	336.7	328.7	328.7	328.7	328.7
3.86	85.0	71.2	331.8	334.3	334.3	3.87	112.2	0.771	338.6	339.6	339.6	332.6	332.6	332.6	332.6
4.00	82.7	73.8	333.7	336.2	336.2	4.01	112.2	0.752	341.5	342.5	342.5	335.1	335.1	335.1	335.1
4.50	73.1	83.0	334.4	336.9	336.9	4.51	112.0	0.672	343.4	343.4	343.4	337.0	337.0	337.0	337.0
5.00	60.8	92.8	314.5	316.5	316.5	5.03	112.4	0.565	323.3	321.3	321.3	317.8	317.8	317.8	317.8
5.25	53.2	97.2	289.3	292.8	292.8	5.27	112.3	0.500	297.2	295.2	295.2	293.0	293.0	293.0	293.0

Table 10-8

Comparison of Power Readings by Meter Types
for R-C Load Using a Sinusoidal Source

I _L (AMPS)	P-3 #1		P-3 #2		C.H. #1		C.H. #2	
	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)
0.50	+2.0	+3.7	--	--	--	--	+1.5	+2.8
0.78	+2.0	+2.4	--	--	--	--	+2.0	+2.3
0.99	+1.0	+0.9	--	--	--	--	+2.5	+2.3
1.53	+1.0	+0.6	--	--	--	--	+2.0	+1.2
2.03	+4.0	+1.8	--	--	--	--	+2.0	+0.9
2.50	--	--	+2.5	+0.9	--	--	+2.0	+0.7
2.99	--	--	+4.5	+1.5	--	--	+2.5	+0.8
3.52	--	--	+2.5	+0.8	--	--	+1.0	+0.3
3.86	--	--	+2.4	+0.7	--	--	+1.0	+0.3
4.00	--	--	+2.5	+0.7	--	--	+1.0	+0.3
4.50	--	--	+2.5	+0.7	--	--	--	--
5.00	--	--	+2.0	+0.6	+2.0	+0.6	--	--
5.25	--	--	+3.5	+1.2	+2.0	+0.7	--	--

Table 10-9

Comparison of Power Readings for an R-C Load Using a Sinusoidal Source

I _L (AMPS)	P-3		C.H.			W.H.M.		
	AVG. (WATTS)	AVG. (WATTS)	DIFF. (WATTS)	DIFF. (%)	(WATTS)	DIFF. (WATTS)	DIFF. (%)	
0.50	55.0	55.3	+0.3	+0.5	50.0	-5.0	-9.1	
0.78	87.9	87.0	-0.9	-1.0	80.4	-7.5	-8.5	
0.99	109.9	111.3	+1.4	+1.3	104.0	-5.9	-5.4	
1.53	169.3	172.9	+3.6	+2.1	164.4	-4.9	-2.9	
2.03	225.7	226.9	+1.2	+0.5	218.2	-7.5	-3.3	
2.50	267.8	274.8	+7.0	+2.6	266.7	-1.1	-0.4	
2.99	304.6	310.0	+5.4	+1.8	301.2	-3.4	-1.1	
3.52	329.8	336.2	+6.4	+1.9	328.7	-1.1	-0.3	
3.86	333.0	339.1	+6.1	+1.8	332.6	-0.4	-0.1	
4.00	335.0	342.0	+7.0	+2.1	335.1	+0.1	0.0	
4.50	335.7	343.4	+7.7	+2.3	337.0	+1.3	+0.4	
5.00	315.5	322.3	+6.8	+2.2	317.8	+2.3	+0.7	
5.25	291.1	296.3	+5.2	+1.8	293.0	+1.9	+0.6	

CHAPTER 11

MEASURING SINGLE-PHASE POWER USING A HALF-WAVE RECTIFIED SOURCE

This chapter discusses the experimental results obtained using a half-wave rectified source with a high power-factor load, a R-L load and a R-C load. It draws individual conclusions for each type of load by comparing the power readings by meter types and by comparing the average power readings of the P-3 meters, the C.H. meters and the W.H.M. The chapter concludes by summarizing the conclusions obtained using the half-wave rectified source with the various loads.

11.1 High Power-Factor Load Test

This test was conducted using a half-wave rectified source and the high power-factor load. The results of this test are as follows:

a) Comparison of Power Readings by Meter Types

(reference table 11.1 and 11.2)

- (1) The P-3 meter readings were within ± 2 per cent of each other for all power measurements except for the low power measurements below 100 watts. Again, the effect of limiting error at the low end of the P-3 meter scale was indicated, as a 3 watt difference in power resulted in a 7 per cent difference in meter readings.
- (2) The C.H. meter readings were within ± 4 digits and ± 3 per cent of each other for all power measurements except for the low power measurements below 100 watts. The effect of

limiting error at the low end of the C.H. meter range was indicated, as a 2.5 watt difference in power resulted in a 6 per cent difference in meter readings.

(3) Surprisingly, the "Input Overload" light lit for C.H. meter readings of composite ac and dc current values greater than 4.00 amps. This is an indication that the C.H. input network is sensitive to signals with a large dc component and thus the specified input range of 0 to 5 amps may need to be clarified to state that a non-sinusoidal signal containing a large dc component, such as with a half-wave rectified source, may result in an Input Overload condition at composite current values less than 5 amps. Analysing the C.H. readings indicated that these readings were within the expected range.

(b) Comparison of Average Power Readings (reference table 11-3)

(1) The C.H. AVG. power readings were between 0 to 3.2 per cent higher than the P-3 AVG. readings.

(2) The W.H.M. average power readings were between 0 to 3 per cent lower than the P-3 AVG. readings for power readings greater than 100 watts. At power readings less than 100 watts the inductive effect of the high power-factor load was significant and a per cent difference of -11.7 per cent was observed. Generally the W.H.M. performed similarly to the sinusoidal source case.

11.2 Resistive-Inductive (R-L) Load Test

This test was conducted using a half-wave rectified source and the high power-factor load in series with a 65 milli-henry inductance. The results of this test are as follows:

a) Comparison of Power Readings by Meter Types

(reference tables 11-4 and 11-5)

(1) The P-3 meter readings were within ± 2.5 per cent of each other for all power measurements.

(2) The C.H. meter readings were within ± 2 digits and ± 3 per cent of each other for all power measurements.

b) Comparison of Average Power Readings (reference table 11-6)

(1) The C.H. AVG. power readings were between 0 to 3.4 per cent higher than the P-3 AVG. readings.

(2) The W.H.M. average power readings were between 0 to 2.5 per cent lower than the P-3 AVG. readings for power readings greater than 112 watts. At power readings less than 112 watts the inductive effect of the high power-factor load was significant and a per cent difference of -16.1 per cent was observed. Generally the W.H.M. performed similarly to the sinusoidal case up to a load power value of 225 watts.

11.3 Resistive-Capacitive (R-C) Load Test

This test was conducted using a half-wave rectified source and the high power-factor load in series with a 140 micro-farad capacitance. There are no results for this test as the capacitor presented an infinite impedance to the circuit and no ac current component flowed.

The capacitor charged up to $\sqrt{2}$ times the rms line voltage. The actual voltage across the capacitor was 156.8 V_{dc} and the power consumed in the circuit was 3.7 watts.

11.4 Conclusions

The results of using a half-wave rectified source with a varying load while measuring the average power in the test circuit with the P-3's, the C.H.'s and the W.H.M. are as follows:

- a) The P-3 wattmeter readings were generally within ± 2.5 per cent of each other for all power measurements except at very low power readings of less than 50 watts.
- b) The C.H. wattmeter readings were generally within ± 4 digits and ± 3 per cent of each other for all power measurements except at very low power readings of less than 100 watts. The maximum per cent difference between C.H. meters was 5.9 per cent and the maximum per cent difference between the C.H. AVG. readings and the P-3 AVG. readings was +3.4 per cent.
- c) The W.H.M. readings compared to the P-3 AVG. readings were between 0 to 3 per cent lower for power readings greater than 112 watts. At power readings less than 112 watts the inductive effect of the high power-factor load was significant and a per cent difference of up to -16.1 per cent was observed. Generally the W.H.M. performed similarly to the sinusoidal case and had a tendency to improve in per cent difference between power readings as load power was increased. This reduction in per cent difference in power readings between the W.H.M. and the P-3 AVG. reading was

primarily a result of improved accuracy of the W.H.M. with increased power.

- d) Surprisingly, the "Input Overload" light lit for the C.H. meter readings of composite ac and dc current values greater than 4.00 amps. This is an indication the the C.H. input network is sensitive to signals with a large dc component and thus the specified input range of 0 to 5 amps may need to be clarified to state that a nonsinusoidal signal containing a large dc component, such as with a half-wave rectified source, may result in an Input Overload condition at composite current values of less than 5 amps. It should also be noted that analysing the C.H. readings when this Input Overload condition existed indicated that the power readings were still within the expected range and were less than 4 per cent high compared to the P-3 W.G. readings.
- e) Since the W.H.M. does not measure dc power it was expected that the power readings for the half-wave rectified source would be much lower than the values measured by the P-3 meters. Based on this limited testing, this was not the case. The only answer for this apparent contradiction was that the voltage component was always sinusoidal and that the dc component of current did not cause a significant effect on the current coil fluxes. A more detailed investigation into the operation of the W.H.M. when large dc voltage and current components are either individually present or jointly present should be looked at in the future.

Table 11-1

Measuring Single-Phase Power for a High Power-Factor Load Using a Half-Wave Rectified Source

I _L A.C. (AMPS)	I _L D.C. (AMPS)	I _L TOTAL (AMPS)	V _{LOAD} TOTAL (VOLTS)	P-3 #1		P-3 #2		C.H. #1			C.H. #2		W.H.M. P CORR. (WATTS)
				CORR. (WATTS)	CORR. (WATTS)	I ₅ (AMPS)	V ₂₀₀ (VOLTS)	P.F. 200	P ₂₀₀ CORR.	P ₂₀₀ CORR.	P ₂₀₀ CORR.		
0.46	0.32	0.56	80.0	45.0	42.0	0.51	114.1	0.508	42.5	45.0	38.4		
0.81	0.65	1.04	79.7	84.9	82.9	1.02	114.2	0.510	83.0	86.0	78.0		
1.20	0.97	1.54	79.4	122.8	122.8	1.53	114.1	0.517	122.9	125.9	120.9		
1.54	1.28	2.02	79.0	161.7	160.7	2.02	114.1	0.528	164.9	167.9	157.3		
1.96	1.60	2.53	78.5	200.5	202.5	2.54	114.0	0.520	203.3	206.8	195.5		
2.33	1.90	3.01	78.1	238.3	240.3	3.00	113.9	0.523	240.7	244.7	237.9		
2.68	2.18	3.45	77.7	273.5	276.0	3.48	113.9	0.528	279.7	283.7	272.1		
3.10	2.52	4.00	77.2	315.2	318.7	4.01	113.9	0.527	322.5	325.5	314.1		
3.48	2.84	4.49	76.7	351.4	356.4	4.50	113.5	0.530	360.4	364.4	356.6		
3.87	3.16	5.00	76.1	390.0	394.5	5.02	113.7	0.530	400.3	404.3	395.8		

Note: 1) xxx.x for C.H. #1 and C.H. #2 P₂₀₀ CORR. power readings are subject to error as the "INPUT OVERLOAD" light was lit; however, readings appear to be within the expected range.

Table 11-2
 Comparison of Power Readings by Meter Types
 for a High Power-Factor Load Using a Half-Wave Rectified Source

I _L (AMPS)	P-3 #1		P-3 #2		C.H. #1		C.H. #2	
	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)
0.51	+3.0	+7.1	--	--	--	--	+2.5	+5.9
1.02	+2.0	+2.4	--	--	--	--	+3.0	+3.6
1.53	--	--	--	--	--	--	+3.0	+2.4
2.02	+1.0	+0.6	--	--	--	--	+3.0	+1.8
2.54	--	--	+2.0	+1.0	--	--	+3.5	+1.7
3.00	--	--	+2.0	+0.8	--	--	+4.0	+1.7
3.48	--	--	+2.5	+0.9	--	--	+4.0	+1.4
4.01	--	--	+3.5	+1.1	--	--	+3.0	+0.9
4.50	--	--	+5.0	+1.4	--	--	+4.0	+1.1
5.02	--	--	+4.5	+1.2	--	--	+4.0	+1.0

Table 11-3

Comparison of Power Readings for a High Power-Factor Load
Using a Half-Wave Rectified Source.

I _L (AMPS)	P-3		C. H.			W. H. M.		
	AVG. (WATTS)		AVG. (WATTS)	DIFF. (WATTS)	DIFF. (%)	(WATTS)	DIFF. (WATTS)	DIFF. (%)
0.51	43.5		43.8	+0.3	+0.7	38.4	-5.1	-11.7
1.02	83.9		84.5	+0.6	+0.7	78.0	-5.9	-7.0
1.53	122.8		124.4	+1.6	+1.3	120.9	-1.9	-1.5
2.02	161.2		166.4	+5.2	+3.2	157.3	-3.9	-2.4
2.54	201.5		205.1	+3.6	+1.8	195.5	-6.0	-3.0
3.00	239.3		242.7	+3.4	+1.4	237.9	-1.4	-0.6
3.48	274.8		281.7	+6.9	+2.5	272.1	-2.7	-1.0
4.01	317.0		<u>324.0</u>	+7.0	+2.5	314.1	-2.9	-0.9
4.50	353.9		<u>362.4</u>	+8.5	+2.4	356.6	-2.7	-0.8
5.02	392.3		<u>402.3</u>	+10.0	+2.5	395.8	-3.5	-0.9

Note: 1) xxx.x for C. H. AVG. watts reading is subject to error as "INPUT OVERLOAD" light was lit; however readings appear to be within expected range.

Table 11-4
 Measuring Single-Phase Power for a
 Resistive-Inductive (R-L) Load Using a Half-Wave Rectified Source

I _L A.C. (AMPS)	I _L D.C. (AMPS)	I _L TOTAL (AMPS)	V _{LOAD} TOTAL (VOLTS)	P-3 #1		P-3 #2		C.H. #1			C.H. #2		W.H.M. P CORR. (WATTS)
				CORR. (WATTS)	CORR. (WATTS)	I ₅ (AMPS)	V ₂₀₀ (VOLTS)	P.F. 200	P ₂₀₀ CORR.	P ₂₀₀ CORR.	P ₂₀₀ CORR.		
0.42	0.31	0.52	78.1	42.0	41.0	0.51	114.0	0.507	41.0	42.0	34.8		
0.79	0.61	1.02	74.3	78.9	78.9	1.03	113.5	0.508	78.0	80.0	72.9		
1.14	0.97	1.50	70.5	108.8	109.3	1.51	113.3	0.508	109.9	111.9	103.9		
1.50	1.30	1.98	66.5	136.2	138.7	2.00	113.1	0.497	139.9	141.9	134.0		
1.86	1.65	2.49	62.1	164.0	164.0	2.51	112.8	0.488	166.8	167.8	160.2		
2.19	2.00	2.97	57.9	184.3	185.8	3.00	112.7	0.474	187.7	189.7	181.2		
2.53	2.38	3.47	52.4	197.0	199.5	3.51	112.6	0.451	202.7	203.2	194.9		
2.85	2.74	3.95	47.0	206.7	208.2	4.01	112.5	0.427	211.5	211.5	204.9		
3.19	3.13	4.47	41.8	211.9	214.4	4.52	112.4	0.397	217.4	217.4	212.9		
4.49	3.48	4.93	37.6	214.5	216.5	4.99	112.6	0.376	223.3	222.3	214.5		

Note: 1) xxx.x for C.H. #1 and C.H. #2 P₂₀₀CORR. power readings are subject to error as the "INPUT OVERLOAD" light was lit; however, readings appear to be within the expected range.

Table 11-5
 Comparison of Power Readings by Meter Types for an
 R-L Load Using a Half-Wave Rectified Source

I _L (AMPS)	P-3 #1		P-3 #2		C.H. #1		C.H. #2	
	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)
0.51	+1.0	+2.4	--	--	--	--	+1.0	+2.4
1.03	--	--	--	--	--	--	+2.0	+2.6
1.51	--	--	+0.5	+0.5	--	--	+2.0	+1.8
2.00	--	--	+2.5	+1.8	--	--	+2.0	+1.4
2.51	--	--	--	--	--	--	+1.0	+0.6
3.00	--	--	+1.5	+0.8	--	--	+2.0	+1.1
3.51	--	--	+2.5	+1.3	--	--	+0.5	+0.2
4.01	--	--	+1.5	+0.7	--	--	--	--
4.52	--	--	+2.5	+1.2	--	--	--	--
4.99	--	--	+2.0	+0.9	+1.0	+0.4	--	--

Tabl. 11-6

Comparison of Power Readings for an R-L Load
Using a Half-Wave Rectified Source.

I _L (AMPS)	P-3		C.H.			W.H.M.		
	AVG. (WATTS)		AVG. (WATTS)	DIFF. (WATTS)	DIFF. (%)	(WATTS)	DIFF. (WATTS)	DIFF. (%)
0.51	41.5		41.5	0.0	0.0	34.8	-6.7	-16.1
1.03	78.9		79.0	+0.1	+0.1	72.9	-6.0	- 7.6
1.51	109.1		110.9	+1.8	+1.6	103.9	-5.2	- 4.8
2.00	137.5		140.9	+3.4	+2.5	134.0	-3.5	- 2.5
2.51	164.0		167.3	+3.3	+2.0	160.2	-3.8	- 2.3
3.00	185.1		188.7	+3.6	+1.9	181.2	-3.9	- 2.1
3.51	198.3		203.0	+4.7	+2.4	194.9	-3.4	- 1.7
4.01	207.5		211.5	+4.0	+1.9	204.9	-2.6	- 1.3
4.52	213.2		217.4	+4.2	+2.0	212.9	-0.3	- 0.1
4.99	215.5		222.8	+7.3	+3.4	214.5	-1.0	- 0.5

Note: 1) xxx.x for C.H. AVG. watts reading is subject to error as "INPUT OVERLOAD" light was lit; however, readings appear to be within the expected range.

CHAPTER 12

MEASURING SINGLE-PHASE POWER USING A THYRISTOR-CONTROLLED SOURCE

This chapter discusses the experimental results obtained using a bidirectional thyristor-controlled (triac) source with a high power-factor load, a R-L load and a R-C load. It draws individual conclusions for each type of load by comparing the power readings by meter types and by comparing the average power readings of the P-3 meters, the C.H. meters and the W.H.M. The chapter concludes by summarizing the conclusions obtained using the thyristor-controlled source with the various loads.

12.1 High Power Factor Load Test

This test was conducted using a bidirectional thyristor-controlled source set at a firing angle of 90 degrees and the high power-factor load. The results of this test are as follows:

a) Comparison of Power Readings by Meter Types

(reference table 12.1 and 12.2)

- (1) The P-3 meter readings were within ± 2.5 per cent of each other for all power measurements.
- (2) The C.H. meter readings were within ± 3 digits and ± 2.5 per cent of each other for all power measurements except at the low power measurement of 40 watts.
- (3) Surprisingly, again, the "Input Overload" light lit for the C.H. meter readings for current values greater than

4.00 amps. It appears from this indication that the C.H. meters are sensitive not only to large dc components but to signals that are nonsinusoidal. As was the case with the Input Overload condition of chapter 11, the actual power measurements were within the expected range and didn't vary by more than 3.2 per cent greater than the P-3 AVG. meter readings.

(4) Generally, the results of this test were similar to the results obtained for the sinusoidal source of Chapter 10.

b) Comparison of Average Power Readings

(reference table 12-3)

(1) The C.H. AVG. power readings were between 0.5 and 3.2 per cent higher than the P-3 AVG. readings.

(2) The W.H.M. average power readings ranged from 11.6 per cent lower to 0.9 per cent higher than the P-3 AVG. readings. This result was very similar to the result obtained with a sinusoidal source and a R-C load. The results of this test indicate that for a high-power factor load, especially as the load becomes mostly resistive that the W.H.M. has a tendency to speedup. This conclusion is in agreement with reference 36, in which the article states that the W.H.M. has a tendency to speed-up with nonsinusoidal currents. The results of this test are not conclusive, as different results occurred with the R-L load of section 12.2.

12.2 Resistive-Inductive (R-L) Load Test

This test was conducted using a bidirectional thyristor-controlled source set at a firing angle of 90 degrees and the high power-factor load in series with a 65 milli-henry inductance. The results of this test are as follows:

a) Comparison of Power Readings by Meter Types

(reference tables 12-4 and 12-5)

- (1) The P-3 meter readings were within ± 2 per cent of each other for all power measurements except for the reading at 4.51 amps. The overall power readings for this test were less than 125 watts which resulted in all the power measurements being taken at the low end of the P-3 meter scale. As a result of these low power values it was hard to read differences in power when using the P-3 meters.
- (2) The C.H. meter readings were within ± 2 digits and ± 5.3 per cent for all power measurements taken up to the 4.00 amp setting. At current values greater than 4.00 amps, C.H. #1 was affected significantly by the increase in inductance in the circuit. The maximum per cent difference between C.H. #1 and C.H. #2 was 10.6 per cent. This result is similar to the result obtained for the sinusoidal source and R-L load (reference table 10-5).

b) Comparison of Average Power Readings

(reference table 12-6)

- (1) The C.H. AVG. power readings were between 1.7 to 5.4 per cent higher than the P-3 AVG. readings. The main difference occurred at low power values (less than 50

watts) and was due primarily to the increased inductance in the circuit.

- (2) The W.H.M. average power readings were generally between 3 to 8 per cent lower than the P-3 AVG. readings for all values except for the low power readings below 75 watts. At these low power readings the W.H.M. indicated a significantly smaller reading of 10.8 to 16.4 per cent lower than the P-3 AVG. reading. These lower readings were a result of the increased circuit inductance and a corresponding lower power-factor at these low power values.

12.3 Resistive-Capacitive (R-C) Load Test

This test was conducted using a bidirectional thyristor-controlled source set at a firing angle of 90 degrees and the high power-factor load in series with a 140 micro-farad capacitance. The results of this test are as follows:

a) Comparison of Power Readings by Meter Types

(reference table 12-7 and 12-8)

- (1) The P-3 meter readings were within ± 2 per cent of each other for all power measurements.
- (2) The C.H. meter readings were within ± 3 digits and ± 2.5 per cent of each other for all power measurements except at the low power measurement of 41 watts.
- (3) The Input Overload light again came on for the C.H. meters at a current value of 3.60 amps and 250 watts. It appears from this indication that the C.H. meters are sensitive to nonsinusoidal signals. Again, the power reading at 3.60

amps was only 2 per cent higher than the C.H. AVG. reading.

(4) The test current for this test was only taken up to values of 3.60 amps because the thyristor-controlled source would not hold the 90 degree firing angle and would resort back to sinusoidal operation as the high power-factor load was varied.

(5) Generally the results of this test were very similar to the results obtained for the sinusoidal source of Chapter 10.

b) Comparison of Average Power Readings (reference table 12-9)

(1) The C.H. AVG. power readings were between 0.7 to 5.0 per cent higher than the P-3 readings. The main difference occurred at low power values (less than 50 watts).

(2) The W.H.M. average power readings ranged from 10 per cent lower to 1 per cent higher than the P-3 AVG. readings. The W.H.M. showed a tendency to increase in value compared to the P-3 AVG. readings as the capacitive reactance became a more significant part of the circuit load. This result was similar to the result obtained for the sinusoidal source and R-C load of Chapter 10.

12.4 Conclusions

The results of using a bidirectional thyristor-controlled source with a varying load while measuring the average power in the test circuit with the P-3's, the C.H.'s and the W.H.M. are as follows:

- a) The P-3 wattmeter readings were generally within ± 2.5 per cent of each other for all power measurements.
- b) The C.H. wattmeter readings were generally within ± 3 digits and ± 2.5 per cent for all types of loads. There was a slight increase in per cent difference between the C.H. AVG. readings and the P-3 AVG. readings at low power (less than 50 watts) but this was primarily due to limiting error at the low end of the meter ranges. The only significant difference occurred with C.H. #1 when measuring the R-L load at current values above 4.00 amps. The test data of tables 12-5 and 12-6 indicate that C.H. #1 was affected by changes in power-factor, especially at a lagging power-factor of 0.102 where the per cent difference between C.H. #1 and either C.H. #2 or the P-3 meters increased to + 10.6 per cent. This result is similar to the result obtained for the sinusoidal source and R-L load of Chapter 10.
- c) The W.H.M. readings compared to the P-3 AVG. wattmeter readings varied considerably depending on the type of load. For the high power-factor load, the variation between the W.H.M. and the P-3 AVG. reading ranged from 11.6 per cent lower to 0.9 per cent higher. This result was very similar to the result obtained with a sinusoidal source and an R-C load. The results of the high power-factor load test indicated that the W.H.M. has a tendency to speedup with nonsinusoidal currents. This conclusion was in agreement with statements made in reference 36 in regards to the W.H.M. having a tendency to speed-up with non-sinusoidal currents. The results of this high power-factor load test with regard to the

W.H.M. speeding-up with non-sinusoidal current is not conclusive as different results occurred with the R-L load. For the R-L load, the variation between the W.H.M. and the P-3 AVG. reading was generally lowered an additional 3 per cent and the range of this variation was between -2.5 to -8 per cent. This increased difference was a result of the increased inductance in the circuit which caused a considerable lagging power-factor. This lagging power-factor had a significant effect at low power readings as the difference between the W.H.M. and the P-3 AVG. reading increased to -16.4 per cent. For the R-C load, the variation between the W.H.M. and the P-3 AVG. reading varied between a -10 per cent to a + 1 per cent. Again, this result indicated that the W.H.M. is affected by power-factor. The effect of increasing capacitive reactance was that the W.H.M. reading increased and finally became greater than the P-3 reading. This speeding-up of the W.H.M. occurs with a capacitive load and was similar to the results obtained with the sinusoidal source and R-C load of Chapter 10.

- d) Surprisingly, the "Input Overload" light lit for the C.H. meter readings for current values greater than 4.00 amps for the high power-factor load and for current values greater than 3.6 amps for the R-C load. The lighting of the Input Overload light appears to indicate that the C.H. meters are sensitive not only to large dc components but also to non-sinusoidal signals above a current range of 3.6 amps. As was the case with the Input Overload condition of Chapter 11, the actual

power measurements were within the expected range and didn't vary by more than 4.8 per cent greater than the P-3 AVG. meter readings.

Table 12-1

Measuring Single-Phase Power for a High Power-Factor Load Using a Thyristor-Controlled Source

I _L (AMPS)	V _{LOAD} (VOLTS)	P-3 #1		C.H. #1			C.H. #2		W.H.M. PCORR. (WATTS)
		CORR. (WATTS)	CORR. (WATTS)	I ₅ (AMPS)	V ₂₀₀ (VOLTS)	P.F. 200	P ₂₀₀ CORR.	P ₂₀₀ CORR.	
0.50	82.8	40.0	41.0	0.49	113.9	0.529	40.0	42.0	35.8
1.00	82.4	81.4	80.9	1.00	113.9	0.542	81.0	83.0	74.4
1.50	81.7	121.8	121.8	1.51	113.5	0.540	122.9	124.9	116.3
2.01	80.5	162.2	162.7	2.03	113.6	0.538	164.4	165.9	156.8
2.50	79.9	207.0	203.5	2.53	113.6	0.532	204.8	207.8	196.8
3.00	79.5	240.3	242.3	3.03	113.5	0.530	244.7	246.7	235.5
3.49	79.2	280.0	283.0	3.52	113.0	0.531	286.7	288.7	282.5
4.01	78.9	318.2	321.2	4.05	112.6	0.533	<u>330.0</u>	<u>330.0</u>	319.7
4.51	78.0	357.9	360.9	4.57	112.6	0.533	<u>369.4</u>	<u>370.4</u>	359.0
5.01	78.1	398.0	404.0	5.07	112.3	0.537	<u>413.3</u>	<u>413.3</u>	404.7

Note: 1) xxx.x for C.H. #1 and C.H. #2 P₂₀₀ CORR. power readings are subject to error as the "INPUT OVERLOAD" light was lit; however, readings appear to be within the expected range.

Table 12-2
 Comparison of Power Readings by Meter Types for a
 High Power-Factor Load Using a Thyristor-Controlled Source

I _L (AMPS)	P-3 #1		P-3 #2		C.H. #1		C.H. #2	
	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)
0.50	--	--	+1.6	+2.5	--	--	+2.0	+5.0
1.00	+0.5	+0.6	--	--	--	--	+2.0	+2.5
1.50	--	--	--	--	--	--	+2.0	+1.6
2.01	--	--	+0.5	+0.3	--	--	+1.5	+0.9
2.50	+3.0	+1.7	--	--	--	--	+3.0	+1.5
3.00	--	--	+2.0	+0.8	--	--	+2.0	+0.8
3.49	--	--	+3.0	+1.1	--	--	+2.0	+0.7
4.01	--	--	+3.0	+0.9	--	--	--	--
4.51	--	--	+3.0	+0.6	--	--	+1.0	+0.3
5.01	--	--	+3.6	+1.5	--	--	--	--

Table 12-3

Comparison of Power Readings for a High Power-Factor Load Using a thyristor-Controlled Source

I _L (AMPS)	P-3	C.H.			W.H.M.		
	AVG. (WATTS)	AVG. (WATTS)	DIFF. (WATTS)	DIFF. (%)	(WATTS)	DIFF. (WATTS)	DIFF. (%)
0.50	40.5	41.0	+0.5	+1.2	35.8	-4.7	-11.6
1.00	81.2	82.0	+0.8	+1.0	74.4	-6.8	-8.4
1.50	121.8	123.9	+2.1	+1.7	116.3	-5.5	-4.5
2.01	162.5	165.2	+2.7	+1.7	156.8	-5.7	-3.5
2.50	205.3	206.3	+1.0	+0.5	196.8	-8.5	-4.1
3.00	241.5	245.7	+4.4	+1.8	235.5	-5.8	-2.4
3.49	281.5	287.7	+6.2	+2.2	282.5	-1.0	-0.4
4.01	319.7	<u>330.0</u>	+10.3	+3.2	319.7	0.0	0.0
4.51	359.4	369.9	+10.5	+2.9	359.0	-0.4	-0.1
5.01	401.0	<u>413.3</u>	+12.3	+3.1	404.7	+3.7	+0.9

Table 12-4

Measuring Single-Phase Power for a Resistive-Inductive
(R-L) Load Using A Thyristor-Controlled Source

I _L (AMPS)	V _{LOAD} (VOLTS)	V _{IND} (VOLTS)	P-3 #1		P-3 #2 CORR. (WATTS)	C.H. #1				C.H. #2		W.H.M. P CORR. (WATTS)
			CORR. (WATTS)			I ₅ (AMPS)	V ₂₀₀ (VOLTS)	I.F. 200	P ₂₀₀ CORR.	P ₂₀₀ CORR.	P ₂₀₀ CORR.	
0.50	72.6	24.3	37.0		37.0	0.50	113.5	0.543	38.0	40.0	33.0	
1.00	63.2	39.9	67.9		66.9	1.01	113.1	0.546	68.0	70.0	62.0	
1.50	55.7	53.2	91.8		91.8	1.51	113.0	0.543	92.9	93.9	85.3	
2.00	49.4	66.0	110.7		110.7	2.01	112.9	0.509	113.9	113.9	104.5	
2.50	41.1	76.6	120.0		120.5	2.53	112.5	0.461	122.8	122.8	114.2	
3.00	32.4	85.5	118.3		118.3	3.03	112.4	0.400	121.7	120.7	112.9	
3.50	22.6	94.1	106.0		106.0	3.56	112.6	0.304	109.7	108.7	98.8	
4.00	13.2	101.7	85.7		84.7	4.06	112.4	0.214	88.5	86.5	83.1	
4.51	5.5	107.5	65.4		62.9	4.57	112.5	0.141	67.4	64.4	55.7	
4.78	1.2	110.6	48.0		47.0	4.84	112.6	0.102	52.3	47.3	39.7	

Table 12-5

Comparison of Power Readings by Meter Types for an R-L Load Using a Thyristor-Controlled Source

I _L (AMPS)	P-3 #1		P-3 #2		C.H. #1		C.H. #2	
	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)
0.50	--	--	--	--	--	--	+2.0	+5.3
1.00	+1.0	+1.5	--	--	--	--	+2.0	+2.9
1.50	--	--	--	--	--	--	+1.0	+1.1
2.00	--	--	--	--	--	--	--	--
2.50	--	--	+0.5	+0.4	--	--	--	--
3.00	--	--	--	--	+1.0	+0.8	--	--
3.50	--	--	--	--	+1.0	+0.9	--	--
4.00	+1.0	+1.2	--	--	+2.0	+2.3	--	--
4.51	+2.5	+4.0	--	--	+3.0	+4.7	--	--
4.78	+1.0	+2.1	--	--	+5.0	+10.6	--	--

Table 12-6

Comparison of Power Readings for a R-L Load
Using a Thyristor-Controlled Source

I _L (AMPS)	P-3	C.H.			W.H.M.		
	AVG. (WATTS)	AVG. (WATTS)	DIFF. (WATTS)	DIFF. (%)	(WATTS)	DIFF. (WATTS)	DIFF. (%)
0.50	37.0	39.0	+2.0	+5.4	33.0	-4.0	-10.8
1.00	67.4	69.0	+1.6	+2.4	62.0	-5.4	-8.0
1.50	91.8	93.4	+1.6	+1.7	85.3	-6.5	-7.1
2.00	110.7	113.9	+3.2	+2.9	104.5	-6.2	-5.6
2.50	120.3	122.8	+2.5	+2.1	114.2	-6.1	-5.1
3.00	118.3	121.2	+2.9	+2.5	112.9	-5.4	-4.6
3.50	106.0	109.2	+3.2	+3.0	98.8	-7.2	-6.8
4.00	85.2	87.5	+2.3	+2.7	83.1	-2.1	-2.5
4.51	64.2	65.9	+1.7	+2.6	55.7	-8.5	-13.2
4.78	47.5	49.8	+2.3	+4.8	39.7	-7.8	-16.4

Table 12-7
 Measuring Single-Phase Power for a Resistive-Capacitive (R-C)
 Load Using a Thyristor-Controlled Source

I _L (AMPS)	V _{LOAD} (VOLTS)	V _C (VOLTS)	P-3 #1		P-3 #2 CORR. (WATTS)	C.H. #1				C.H. #2		W.H.M. P CORR. (WATTS)
			CORR. (WATTS)			I ₅ (AMPS)	V ₂₀₀ (VOLTS)	P.F.-200	P ₂₀₀ CORR.	P ₂₀₀ CORR.	P ₂₀₀ CORR.	
0.50	83.6	7.6	40.0		40.0	0.50	112.9	0.526	41.0	43.0	36.0	
1.00	83.9	15.8	83.9		82.9	1.01	113.6	0.527	83.0	85.0	76.4	
1.31	84.1	20.5	107.8		107.8	1.31	113.9	0.522	109.9	111.4	102.6	
1.45	89.4	23.3	126.8		127.8	1.45	114.0	0.547	128.9	130.9	124.3	
1.73	88.5	27.7	153.7		152.7	1.74	113.6	0.541	152.9	155.9	146.6	
1.98	81.8	30.4	161.7		161.7	2.00	113.7	0.510	163.9	165.9	158.0	
2.46	77.9	36.4	192.5		193.5	2.48	113.8	0.491	195.8	197.3	190.0	
2.99	70.8	42.9	206.3		208.3	3.03	113.9	0.467	210.7	212.2	205.6	
3.60	69.3	50.3	246.0		247.0	3.69	113.9	0.461	250.7	251.7	248.4	

Note: 9) xxx.x for C.H. #1 and C.H. #2 P₂₀₀ CORR. power readings are subject to error as the "INPUT OVER-LOAD" light was lit; however, readings appear to be within the expected range.

Table 12-8

Comparison of Power Readings by Meter Types for an R-C Load Using a Thyristor-Controlled Source

I _L (AMPS)	P-3 #1		P-3 #2		C.H. #1		C.H. #2	
	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)	(WATTS)	(%)
0.50	--	--	--	--	--	--	+2.0	+4.9
1.00	+1.0	+1.2	--	--	--	--	+2.0	+2.4
1.31	--	--	--	--	--	--	+1.5	+1.4
1.45	--	--	+1.0	+0.8	--	--	+2.0	+1.6
1.73	+1.0	+0.7	--	--	--	--	+3.0	+2.0
1.98	--	--	--	--	--	--	+2.0	+1.2
2.46	--	--	+1.0	+0.5	--	--	+1.5	+0.8
2.99	--	--	+2.0	+1.0	--	--	+1.5	+0.7
3.60	--	--	+0.4	+1.0	--	--	+1.0	+0.4

Table 12-9
 Comparison of Power Readings for an R-C Load
 Using a Thyristor-Controlled Source

I _L (AMPS)	P-3	C. H.			W. H. M.		
	AVG. (WATTS)	AVG. (WATTS)	DIFF. (WATTS)	DIFF. (%)	(WATTS)	DIFF. (WATTS)	DIFF. (%)
0.50	40.0	42.0	+2.0	+5.0	36.0	- 4.0	-10.0
1.00	83.4	84.0	+0.6	+0.7	76.4	- 7.0	-8.4
1.31	107.8	110.7	+2.9	+2.7	102.6	- 5.2	-4.8
1.45	127.3	129.9	+2.6	+2.0	124.3	- 3.0	-2.4
1.73	153.2	154.4	+1.2	+0.8	146.6	- 6.6	-4.3
1.98	161.7	164.9	+3.2	+2.0	158.0	- 3.7	-2.3
2.46	193.0	196.4	+3.4	+1.8	190.0	- 3.0	-1.6
2.99	207.3	211.5	+4.2	+2.0	205.6	- 1.7	-0.8
3.60	246.5	251.2	+4.7	+1.9	248.4	+ 1.9	+0.8

Note: xxx.x for C.H. AVG. watts reading is subject to error as the "INPUT OVERLOAD" light was lit; however, the reading appears to be within the expected range.

PART III

THESIS CONCLUSIONS/RECOMMENDATIONS

CHAPTER 13

THESIS CONCLUSIONS/RECOMMENDATIONS

This chapter states the general conclusion drawn from this thesis work as well as summarizing the specific conclusions drawn from the experimental work done in Part II. It concludes by making some specific recommendations concerning the type of meter to use when making single-phase power measurements and by making some specific recommendations concerning possible additional research that can be done with regard to measuring single-phase non-sinusoidal power.

13.1 Thesis Conclusions

The primary objectives of this thesis were to be able to measure accurately single-phase power when non-sinusoidal or dc current components are present and to determine which type of power meters are most accurate and are less affected by these non-sinusoidal or dc current variations. The secondary objectives of this thesis were the following:

- a) to define the basic power definitions associated with sinusoidal power, non-sinusoidal power and power factor.
- b) to become familiar with and understand the basic operation of some of the different metering equipment available for measuring single-phase power and energy.
- c) to define measurement standards and types of measurement errors.

- d) to define the basic definitions for precision and accuracy, especially as applied to power measurements.
- e) to become familiar with and understand the specific operation of the Clarke-Hess digital wattmeter, the General Electric P-3 electrodynamic wattmeter, and the General Electric induction watthour meter.
- f) to become familiar with and understand the factors which affect the accuracy of the Clarke-Hess digital wattmeter, the General Electric P-3 electrodynamic wattmeter, and the General Electric induction watthour meter.
- g) to verify by experimental testing which types of meters give accurate measurement of sinusoidal and non-sinusoidal power.

Considering first the question of whether the secondary objectives of this thesis were met, the answer is yes. The secondary objectives were met through the extensive literature search and through the experimental work done in Part II of this thesis. Generally, it can be concluded that a general knowledge of how power and energy meters work and of what type of errors can exist when taking power measurements, as well as a specific knowledge of the specific operation of the various power and energy meters tested and the factors which affect the accuracy of these meters, was gained in fulfilling these secondary thesis objectives.

Considering now the question of whether the primary objectives of this thesis were met, the answer is yes. The main objectives of this thesis were to be able to measure accurately single-phase sinusoidal and non-sinusoidal power and to determine which types

of power and energy meters are most accurate and are less affected by non-sinusoidal power variations. Considering the first objective of being able to measure accurately single-phase sinusoidal and non-sinusoidal power, the conclusions that were drawn are the following:

a) Accuracy is defined [30] as the quality which characterizes the ability of a measuring instrument to give indications equivalent to the true value of the quantity measured and is expressed in terms of tolerance or uncertainty. Since it was impossible to express the absolute quantity or true value of the power quantities measured in this thesis and since the transfer standard (P-3 electro-dynamometer wattmeter) had a limiting error or tolerance, the only real determination that could be made was a comparative analysis of the various test meters against each other. This comparative method was used in the experimental work in Part II of this thesis and was not expected to give an absolute value of power but was expected to show how a comparative range or relative degree of uncertainty exists between meters of the same type and between meters of different types. The following are the general results of the experimental work:

- (1) The P-3 wattmeter readings were generally within ± 2 per cent of each other for all power readings.
- (2) The C.H. wattmeter readings were generally within ± 3 digits and ± 3 per cent of each other for all power readings.
- (3) The C.H. AVG. power readings were generally 0 to 3 per cent higher than the P-3 AVG. readings.

(4) The W.H.M. averaged power readings compared to the P-3 AVG. power readings varied considerably depending on both the type of source and the type of load used. This difference in readings ranged from 19.6 per cent lower to 0.9 per cent higher.

b) Considering accuracy as defined in a) above and realizing that most power measurements in the field would be conducted in a similar manner, it can be concluded that the P-3 wattmeters and the C.H. wattmeters give accurate indications of the power consumed in a circuit on sinusoidal, non-sinusoidal and half-wave rectified (where a dc component is present) power measurements. The accuracy of the W.H.M., based on the limited testing done in this thesis, is questionable as large variations in averaged power readings did occur, especially at low power (less than 75 watts) readings.

Considering the second main objective of this thesis of being able to determine which types of power and energy meters are most accurate and are less affected by non-sinusoidal power variations, the conclusions that were drawn are the following:

a) The general conclusions concerning the accuracy of the types of meters tested is summarized under the first main objective above. Some additional conclusions concerning the accuracy of the meters tested are:

(1) All meters tested varied non-linearly at times. Meters of the same type would vary (at times being greater or less than the other meter) depending on the type of source, the type of load, or the current value in the circuit. This

variation was not critical but is important in realizing that correction curves for each meter are necessary to accurately compare meters. There were no correction curve available for the C.H. meters or the W.H.M.

(2) The accuracy of the power and energy meters at the low end of their scale is subject to both gross (human) and limiting errors. This limiting error was a factor for all meters tested at values less than 50 watts and was especially noticeable when trying to read and compare the P-3 and the W.H.M. power readings.

b) The general conclusions drawn in determining which meters are affected least by non-sinusoidal power variations are:

(1) The P-3 meters were affected least by non-sinusoidal power variations. The P-3 meters were not affected by either the half-wave rectified or the thyristor-controlled source nor were they affected by changes in load.

(2) The C.H. meters generally responded well to non-sinusoidal power variations. The test data did indicate that C.H. #1 was affected by changes in power-factor during testing with the R-L load. C.H. #1 had a tendency to read noticeably higher than either C.H. #2 or the P-3 meters on R-L loads with both the sinusoidal and the thyristor controlled source.

(3) Surprisingly, the "Input Overload" light lit for the C.H. meter readings of composite ac and dc current values greater than 4.0 amps for the half-wave rectified source. The "Input Overload" light also lit for current values

greater than 4.0 amps for the high power-factor load and for current values greater than 3.6 amps for the R-C load for the thyristor- controlled source. The lighting of the Input Overload light is an indication that the C.H. input network is sensitive not only to signals with a large dc component but also to non-sinusoidal signals above a current range of approximately 3.6 amps. It should be noted, however, that analysing the C.H. readings when this Input Overload condition existed indicated that the power readings were still within the expected range and were less than 5 per cent high compared to the P-3 AVG. reading.

- (4) The W.H.M. seemed to be affected more by the type of load rather than the type of source. As mentioned earlier, the variation in average power readings varied considerably based on the load. This was an indication that the W.H.M. was affected significantly at the low end of its power/energy range by the power-factor of the circuit. Generally, the W.H.M. read considerably lower than the P-3 AVG. reading for the R-L load and had a tendency to read higher than the P-3 AVG. reading for the R-C load. This is a direct indication of what excessive inductive or capacitive reactance can do to the operation of the W.H.M.
- (5) Since the W.H.M. does not measure dc power, it was expected that the power readings for the half-wave rectified source would be much lower than the values measured by the P-3 meters. Based on the limited tests

performed during this thesis work this was not the case. An answer for this apparant contradiction was that the voltage component was always sinusoidal and that the dc component of current did not cause a significant effect on the current coil fluxes. A more detailed investigation into the operation of the W.H.M. when large dc voltage and current components are either individually or jointly presnt should be looked at in the future.

13.2 Thesis Recommendation

The following are some general recommendations regarding the meters used in this thesis as well as some specific recommendations for future research in the area of measuring accurately single-phase power and energy:

General Recommendations:

- a) Generally, this thesis showed that both the P-3 electro-dynamometer wattmeter and the C.H. digital wattmeter can be used to measure accurately single-phase sinusoidal and non-sinusoidal power. The accuracy of the W.H.M. was good at high power readings but varied considerably at low power-factor and low power readings.
- b) Generally, the P-3 wattmeter was the most consistent performing meter used. The variations between the P-3 meters were small and predictable; whereas the variation between C.H. meters for the R-L load were large at current values greater than 4.0 amps.

- c) The P-3 meters offer the advantages of being accurate, of being easy to use, of being capable of operating up to 10 amps and 200 volts, of being compact, and of being able to operate without a power supply. The main disadvantage of the P-3 meter is its poor resolution at low power (less than 50 watts) readings. The cost of the P-3 meter compared to the C.H. digital meter is not available as P-3 meters are no longer manufactured.
- d) The C.H. meters offer the advantages of being accurate, of being capable of operating at various current ranges up to 5 amps and minus voltage ranges up to 1000 volts, of having various power ranges which allow power measurements up to 5000 watts, and of having an expanded power range ($\times 10$) for better resolution at low current and power values. Some disadvantages of C.H. meters are: they have a tendency to drift from calibration, they are more complicated to use, there are more things that can go wrong with them (eg. blown fuse, components are more temperature sensitive), they require a power supply and they are not as compact as the P-3 wattmeter.

Specific Recommendation

- a) It was found from the experimental testing that the C.H. meters developed a problem where the "Input Overload" light lit for current values less than 5 amps for the half-wave rectified and the thyristor-controlled source. This is an indication that the C.H. input network is sensitive not only to signals with a large dc component but also to non-sinusoidal signals above a current range of 3.6 amps. It

seems based on these test results that the specified input range of 0 to 5 amps may need to be clarified to state that a non-sinusoidal signal or a signal with a large dc component may result in an Input Overload condition at composite current values of less than 5 amps.

- b) Since the W.H.M. does not measure dc power, it was expected that the power readings for the half-wave rectified source would be much lower than the values measured with the P-3 meters. Based on the limited tests performed during this thesis work, this was not the case. The effect of dc components on the operation of the W.H.M. caused by half-wave rectified or thyristor-controlled circuits should be investigated further. Much research has been done considering the effects of harmonics on W.H.M. operation but little or no research has been done considering the effect of dc voltage and current components on W.H.M. operation. It would be good to include in this future testing, load side energy measurements where both the voltage and current waves could be non-sinusoidal and contain a dc component.
- c) It was found that excessive inductive reactance would cause the W.P.M. to slow down and that excessive capacitive reactance would cause the W.H.M. to speedup. Since both series and parallel capacitor banks are used for power-factor control on industrial power systems, it would be interesting to investigate if these capacitor banks cause the W.H.M. or industrial complexes to speedup excessively.

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APPENDIX 1

List of Equipment Used in Experimental Work

1. Sources:

- (a) 120 V, 60 Hz single-phase (provided to lab table #4 in room EE 0-2)
- (b) 120 V Bi-directional Thyristor (Triac) Firing Circuit
- (c) 150 V, 8 A, Type FMC 7817-R3210 Diode
- (d) 0-30 V/0-225 mA Variable dc Supply, Hewlett-Packard, Model 721A, SN. 310-17870

2. Digital Meters:

- (a) 0-1000 V/0-5 A Digital V-A-W Meters, Clarke-Hess, Model 255
resistance of 5A current circuit (28 milli-ohms)
resistance of voltage circuit (5 meg-ohms)

Date last calibrated: SN-656 - Dec 80 - C.H. #1
SN-5955- Jun 82 - C.H. #2

- (b) 0-750 Vac/0-1000 V dc/0-10A Digital Multimeter, Fluke, Model 8010A

Date last calibrated: SN #2945475 - Jun 82
SN #2955021 - Feb 83

3. Analog Meters:

- (a) 500/1000/2000 W Electrodynamometer Wattmeters, General Electric Type P-3

resistance of 5 A current coil (80 milli-ohms)
resistance of 10 A current coil (18 milli-ohms)
resistance of 100 V voltage coil (5.5 kilo-ohms)
resistance of 200 V voltage coil (11.0 kilo-ohms)
self-inductance of 5 A current coil (110 micro-henrys)
self-inductance of 10 A current coil (28 micro-henrys)
self-inductance of 100 V voltage coil (5 milli-henrys)
self-inductance of 200 V voltage coil (5 milli-henrys)

Date last calibrated: SN #3227474 - Jun 82- P-3 #2
SN #3671742 - Jun 82- P-3 #1

(b) 240 V/10 A Induction Watthour Meter, General Electric,
Type VM-63-S

FM-5S, Class 10, TA-2.5, Kh-2.4

resistance of current coils in series (50 milli-ohms)
resistance of the voltage coils in parallel (154 ohms)
self-inductance of current and voltage coils (unknown)

Date last calibrated: SN #64-591-823 (Unknown)

4. Electronic Counter, Hewlett-Packard, Model 521C, SN. 2932
5. Filter Reactors (inductors), Triad-Utrad (Four)
rated 8 mH at 10 A dc - resistance (0.05 ohms)
32 mH at 5 A dc - resistance (0.19 ohms)
6. Inertion Capacitors, Westinghouse (Two)
rated 25 F at 600 V dc Type 1818221
7. Bank of Capacitors, Cornell-Dubilier (Fourteen)
rated 10 F at 2000 V dc
8. Non-inductive Shunt
rated 0-5 A at resistance of 0.10 ohms
9. Variable Resistance (Two)
rated 0-110 ohms at 7 A maximum
10. Variable Resistance, Ohmite
rated 0-25 ohms at 6.5 A maximum

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